T.C.
YEDITEPE UNIVERSITY
INSTITUTE OF HEALTH SCIENCES
DEPARTMENT OF PROSTHODONTICS

# THE INFLUENCE OF MULTIPLE CYCLES OF STEAM-STERILIZATION ON THE DELIVERY ACCURACY OF SPRING-STYLE TORQUE WRENCHES

DOCTOR OF PHILOSOPHY THESIS

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APPROVAL

This thesis has been deemed by the jury in accordance with the relevant articles of Yeditepe University Graduate Education and Examinations Regulation and has been approved by Administrative Board of Institute with decision dated ..../..../.... and numbered ..................

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## DECLARATION

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree except where due acknowledgment has been made in the text.

06.06.2024

Alpcan Bilecen, DDS

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| COF | Coefficint of Friction |
| SLA | Sandblasted, Large Grit, Acid-Etched, Implant Surface |
| $S_a$ | Surface Roughness |
| RGD | Arginylglycylaspartic Acid |
| UCLA | Universal Castable Long Abutment |
| CAD | Computer Aided Design |
| CAM | Computer Aided Manufacture |
| Ncm | Newton Cantimeters |
| µm | Micrometer |
| mm | Milimeter |
| nm | Nanometer |
| ºC | Degrees Celsius |

# ABSTRACT

**Bilecen, A. (2024). The Influence of Multiple Cycles of Steam-Sterilization on the Delivery Accuracy of Spring-Type Torque Wrenches. Yeditepe University, Institute of Health Sciences, Department of Prosthodontics, Phd Thesis, Istanbul.**

The objective of this in vitro study was to assess the impact of multiple steam sterilization cycles on torque delivery capabilities. Sixteen new spring-style torque wrenches and their corresponding manual screwdrivers from four distinct manufacturers (MIS, DTI, NTA, and NucleOSS) were selected for evaluating their torque delivery accuracy by tightening the implant-abutment complex with the torque wrench, loosening the system with the same wrench, and then evaluating the loosening torque. The DTI and MIS groups were tested at 30Ncm, while the NTA and NucleOSS groups were tested at 25Ncm. Each torque device (n=4 per manufacturer; 16 in total) was tested 10 times with Instron. Following the manufacturer's guidelines, all torque wrenches went under steam sterilization, which was repeated 100 times. After steam sterilization was completed, the accuracy of all torque wrenches was retested. Descriptive statistical analysis was used and a repeated-measures ANOVA across four different brands as a between-subject comparison was conducted to assess the difference on accuracy among groups. Kruskall-Wallis and a post hoc Dunn's Test were done for pair comparison with absolute torque differences, followed by a chi-square test to assess the 10% difference from target torque values. The after-autoclave target torque and loosening torque value absolute difference averages of the DTI and MIS groups were significantly lower than those of the NTA and NucleOSS groups ($p=0.0001$). There was no statistically significant difference observed between the other groups ($p > 0.05$). The results indicate that the torque delivery values of the wrenches were influenced by multiple steam sterilization cycles, with variations observed across different implant brands but each brand stayed within 10% of their target torque values. Both the DTI and MIS groups maintained better control over their target torque values after autoclaving compared to the NTA and NucleOSS groups.



**Key words**: Dental Implants, Dental Abutments, Sterilization, Torque

## ABSTRACT (Turkish)

**Bilecen, A. (2024). Çoklu Otoklavlama Siklusunun Yay-Tipi Implant Raşetlerinin Torklama Hassassiyetine Etkisi. Yeditepe Üniversitesi, Sağlık Bilimleri Enstitüsü, Protetik Diş Tedavisi Anabilim Dalı, Doktora Tezi, İstanbul.**

Bu in vitro çalışmanın amacı çoklu otoklavlama siklusunun tork raşetlerinin torklama kapasitelerinin üzerindeki etkisini araştırmaktır. On altı adet yeni yay-tipi tork raşeti ve ilgili tork anahtarı (MIS, DTI, NTA, ve NucleOSS) tutarlılıklarını test etmek üzere seçilmiştir. DTI ve MIS grupları 30Ncm'de test edilirken, NTA ve NucleOSS grupları 25Ncm'de Instron ile test edilmiştir. Tork raşeti ile önce implant-abutment bağlantısı sıkıştırıldıktan sonra aynı tork raşeti ile gevşetilmiş ve gevşeme değeri kaydedilmiştir. Her tork raşeti (n=4 her üretici için, toplam 16) 10 sefer test edilmiştir. Ureticinin talimatları doğrultusunda tüm raşetler 100 defa buharlı sterilizasyon siklusununa sokulduktan sonra tekrar test edilmiştir. Sonuçar ANOVA testi ile dört farklı grup denekler arası dağılıma bakılmıştır. Kruskall-Wallis testi ve sonra Dunn's Testi ile deneklerin ikili post hoc kıyaslaması yapılmış olup deneklerin tork verme kapasiteleri karşılaştırılmıştır. Ki-Kare Testi ile de son olarak deneklerin torklarının %10'luk hedefinde kalıp kalmadıklarına ve dağılımlarına bakılmıştır. Otoklavlama sonrası hedef tork ve gevşeme torku arasındaki mutlak farkları DTI ve MIS gruplarında NTA ve ve NucleOSS gruplarına göre önemli derecede düşük bulunmuştur ($p=0.0001$). DTI ve MIS ile NTA ve NucleOSS grupları kendi aralarında tutarlıdır ($p > 0.05$). Tüm gruplar otoklavlanmadan etkilenmiş olup hep bir grup hedef torkunun ortalama olarak %10'u içerisinde kalmayı başarmıştır ancak sonuçlar DTI ve MIS gruplarının daha tutarlı olduğunu göstermektedir.

**Anahtar Kelimeler**: Dental Implantlar, Dental Dayanaklar, Sterilizasyon, Tork

# 1. INTRODUCTION and PURPOSE

Titanium implants have served as a cornerstone in dental practice for over five decades, revolutionizing the treatment landscape for both partial and complete edentulous patients. Their versatility has empowered dentists to offer diverse treatment options, catering to the unique needs of each individual. However, the widespread adoption of dental implants has not been without its repercussions. As these implants became increasingly prevalent, they ushered in a new era of dental care, marked by both advancements and challenges.

The integration of the implant abutment and body involves securing them together using a tightening screw, forming a cohesive unit essential for long-term stability. Clinicians must grasp the mechanics of this implant-abutment complex to ensure optimal treatment outcomes and to minimize the risk of unintentional screw loosening over time. Research has revealed a screw loosening rate ranging from 5.8% to 12.7% after five years, highlighting the importance of meticulous attention to detail and proactive measures to mitigate potential complications in dental implant procedures (1).

Unintentional screw loosening is associated generally with inadequate torque delivery to the abutment screw (2), embedment relaxation (2), inadequate fit of the restoration, poor machining of component, excessive overloading, screw design, and restoration design (3,4). Loosening of the abutment screw may lead to the fracture of the implant and/or the abutment screw, unbalanced distribution of occlusal forces, a micro gap space between the implant and abutment which allows bacteria accumulation and peri-implantitis, then ultimately to the loss of osseointegration (5,6,7). Based on previous studies, inadequate torquing of an implant screw can lead to loosening, fracture, and even apparent screw failure and finally loss the of prosthesis (8). Excess torques can lead to screw loosening, structural deformations of the screw and fracture (9). Therefore, the preset torque value provided by the manufacturer should be applied upon finishing the restoration. Since clinicians are unable to generate the precise amount of torque with a handheld screwdriver, torque wrenches are used to stabilize the implant-abutment complex.

While several in vitro studies have investigated the impact of steam sterilization on torque wrench accuracy, they often simulate torque application manually or without the presence of implant components like the body, abutment, or screw. This study, however, aims to precisely apply torque to the wrench using a machine, facilitating the tightening of the abutment and implant body with the screw, thus providing a more realistic assessment of clinical conditions.

It is important to apply torque to the wrench using a machine and include the actual implant components in the test because it better replicates real-world clinical scenarios. Manual torque application may vary in consistency and force, leading to potential inaccuracies in the results. By using a machine to apply torque consistently and including all relevant implant components, such as the abutment and screw, the study can provide more reliable data on the impact of steam sterilization on torque wrench accuracy in practical dental implant procedures. This ensures that the findings are applicable and informative for clinicians in their daily practice, helping them make informed decisions regarding sterilization protocols and torque application during implant procedures.

The aim of this thesis is to determine the effect of multiple steam sterilization cycles on the efficacy of torque wrenches. Our study aims to investigate the torque delivery values of torque wrenches after undergoing multiple cycles of steam sterilization. A mechanized system will be used to deliver the required amount of torque in order to create the outcome of the evaluation without any possible operator errors. The result of this study will help to decide the reliability of torque wrenches after repetitive exposures to heat and will show the importance of regular maintenance for torque wrenches, which will help prevent inadequate or excessive torque delivery and thereby improve the treatment outcome for a successful long-term prognosis.

The initial null hypothesis posited that there would be no statistically significant difference between the tightening and loosening torque values before the autoclave. The second null hypothesis posited that there would be no statistically significant change in the torque delivery capacities of implant torque wrenches after multiple cycles of steam sterilization. The third null hypothesis stated that there would be no difference between brands in their torque delivery capacities.

# 2. GENERAL INFORMATION

## 2.1. Definition of the Dental Implant

According to The Glossary of Prosthodontic Terms, an implant is any object or material, introduced into the body of a recipient, encompassing alloplastic materials, encapsulated drugs, or tissue (10).

In contemporary dentistry, the decision to replace missing teeth with implants holds significant importance, representing a pivotal advancement in dental care. Implantology is the department that is dedicated to implant planning, implant placing, and developing. A dental implant is an artificial support that is placed partially in the jawbone while reaching into the mouth to provide retention and support to a dental prosthesis or appliance and classified by their design, material, and position (11). Unlike traditional alternatives such as bridges or dentures, implants offer a more permanent and natural-looking solution. They not only restore aesthetics but also provide functional benefits similar to natural teeth, such as improved chewing ability and speech. Moreover, implants contribute to preserving the integrity of the jawbone by stimulating bone growth, which helps prevent bone loss and maintains facial structure over time. This longevity and stability make implants a preferred choice for patients seeking durable and reliable tooth replacement options.

## 2.2. Implant Types

### 2.2.1. Implants by Biocompatibility

Implants are classified into three groups according to their biocompatibilities (12,13)

Biotolerant Implants: Material is not rejected by the host but is surrounded by a fibrous capsule.

Bioinert Implants: Allows bone apposition on the material surface.

Bioactive Implants: Bone regeneration occurs around the material surface and ion exchange with the host allows chemical bonding along the interface.

### 2.2.2. Implants by Material Selection

In the past, materials like gold, silver, aluminum, platin and porcelain were used for implants. However contemporary classifications categorize implants into three groups based on their materials: metals, ceramics, and polymers (12).

#### 2.2.2.1. Metals

Titanium and its alloys are selected for implantation purposes owing to their favorable elastic modulus, which closely resembles that of bone tissue. (12). Pure titanium become oxidized once in contact with oxygen from the atmosphere. This oxidized layer is around 3-10 nm thick and protects the titanium from corrosion, chemical burn, allowing it to be biocompatible and inert (12, 13). The pure titanium material used for dental implants is categorized according to its resistance to corrosion, durability and ductility and is classified from 1 to 5. Class 1 titanium exhibits notable ductility and corrosion resistance but is characterized by lower durability compared to other grades. In contrast, Class 4 titanium boasts the highest level of durability among titanium grades. Therefore, in dental implant applications, Class 4 pure titanium is preferred for its superior durability, ensuring long-lasting performance and reliability (14). Class 5 titanium is an alloy which has the formula $Ti_6Al_4V$ and has high yield strength, is resistant to corrosion, has low elastic modulus and has fatigue characteristics. Due to their great mechanical properties, Class 5 titanium alloys are frequently used as dental implants in the posterior region where the masticatory forces are high (15).

#### 2.2.2.2. Ceramics

In dental implants, a variety of ceramics find application, yet the standout choice favored by many clinicians is plasma-sprayed hydroxyapatite (HA) coated ceramic implants (14). Hydroxyapatite, a compound naturally present in both bone and teeth, endows these implants with exceptional biocompatibility and favorable mechanical properties. Its presence in the body promotes a harmonious integration with surrounding tissues, enhancing overall implant success rates (15).

One of the key advantages of hydroxyapatite-coated implants lies in their osteoconductive properties, which facilitate accelerated bone healing and promote greater implant stability. This characteristic is particularly beneficial in expediting the osseointegration process, ensuring the implant becomes firmly anchored within the bone structure over time. Moreover, when compared to uncoated metal implants, ceramic-coated metal implants exhibit superior cohesive properties. This attribute contributes to enhanced long-term performance and durability, reducing the risk of complications associated with implant failure or loosening (12).

Hydroxyapatite-coated implants are especially preferred in specific clinical scenarios. They excel in regions of the mouth where there may be adverse reactions to metal, such as in patients with metal sensitivity or allergy. Additionally, they are well-suited for use in areas with Type 4 bone density, as well as in newly formed extraction sockets and newly bone-grafted regions. These environments benefit from the enhanced biocompatibility and osteoconductive nature of hydroxyapatite, promoting optimal healing and integration of the implant (16). In summary, the utilization of plasma-sprayed hydroxyapatite coated ceramic implants represent a sophisticated approach in modern implant dentistry, offering a blend of biocompatibility, mechanical strength, and osseointegration supporting properties essential for successful long-term outcomes.

Zirconia, another ceramic compound renowned for its high biocompatibility and exceptional osseointegration capabilities, has emerged as a notable contender in the realm of dental implants. Its advantageous properties make it a preferred choice for implantation in various clinical scenarios (17,18). However, the use of pure zirconium in dentistry is uncommon, as it necessitates several processing steps to render it suitable for dental implant applications. Manufacturers typically employ specific procedures to transform zirconium into zirconia, the form utilized in dental implants. Notably, the chemical composition of zirconia implants can vary between manufacturers, posing challenges in investigating their surface properties and characteristics (15).

Despite these challenges, zirconia implants boast impressive physical properties, including corrosion resistance and a natural tooth-like color. This makes them particularly suitable for use in patients with thin gingival tissues or in the anterior region of the mouth, where aesthetics is paramount.

In essence, zirconia implants offer a promising alternative in implant dentistry, thanks to their biocompatibility, osseointegration capacity, and favorable physical properties. Despite variations in chemical composition among manufacturers, their resilience to corrosion and aesthetic appeal makes them a valuable option for clinicians seeking optimal outcomes in dental implant procedures.

#### 2.2.2.3. Polymers

Various polymers such as polyurethane, polymethyl methacrylate, polyamide fibers and polytetrafluorethylene have been put to use in implant dentistry (19). Although it is said that polymers mimic the movements of periodontal ligaments and distribute the stress to bone at a greater capacity, some researchers reported that polymers may cause immunological reactions due to the lack of adhesion with living tissues (12).

Dental implants can also be grouped into two groups as threaded and non-threaded implants (12). Threads are thought to play a crucial role in both the initial stabilization and the long-term success of dental implants. (19). Threads on the implant increase the primary contact and surface area of the implant body while supporting the stress distribution to bone (12).

### 2.2.3. Implants by Jawbone Relations

Dental implants are classified by their relationship with the jawbone as:

#### 2.2.3.1. Eposteal Dental Implants

These implants are placed between the mucosa and bone. They are preferred on resorbed crestal bone in neighborhoods with important anatomic landmarks.

#### 2.2.3.2. Endosteal Dental Implants

Implants that are placed on one or both the cortical layers of bone on the upper or lower jaw are endosteal dental implants. They provide retention and osseointegration with their macro and micro formations. While today root shaped implants are common, empty cylindrical, blade type, basket type and fin type implants have also been used (20).

#### 2.2.3.3. Transosteal Dental Implants

Implants that are placed on both cortical layers of jawbone. Staple Bone Implant that is placed on mandibular parasymphysis is an example (20).

Other than that, there are endodontic implants which are placed in the jawbone passing through the tooth canal and root apex (22).

### 2.3. Surface Modifications

The average implant-bone contact is around 70-80%, however, according to Albrektsson et al, 60% contact is enough for osseointegration to take place (10,15).

Given this information, augmenting the functional surface area of the implant-bone interface through surface modifications of the implant could potentially enhance the rate of osseointegration and healing. (12,24). Additionally, coating the surface would increase the apposition of bone (25). Surface modifications are grouped as concave and convex modifications. Sandblasting creates a concave surface whereas surface coating creates a convex structure (15).

Surface modifications include machine manipulation, mechanical procedures such as sandblasting, chemical procedures such as acid etching, electrochemical processes such as anodic oxidation, vacuum, thermal and laser processes (26). These procedures increase the porosity on the implant surface, and as a result, boost the cellular activity on the living tissues (24).

The porosities on the implant surface can be divided into three categories: macro, micro and nano porosities. Macro porosities are the differences in implants geometry, macro pores, thread, and the scale ranges from micron to millimeters. The primary stability and long-term stability of the implant have a direct correlation with the macro porosity on the implants surface. Micro porosities alter from 1-10 microns (12). Nano porosities, on the other hand, range from 1-100 nanometers and play a role in osteoblastic adhesion and protein absorption (27).

When an implant is manufactured, it is cleaned thoroughly, decontaminated, and sterilized. Implants with smooth, glazed surfaces provide direct adhesion between the bone tissue and implant body. The disadvantage is the elongated osseointegration rate. The clinical results improve when the implant is applied to regions with sufficient bone density. (28)

Another process used for maximizing the porosity on the implants surface is treatment with hydrochloric and sulfuric acid. This process removes the oxidized layer on the titanium implant, forming a porous layer. This procedure boosts the cellular activity surrounding the implant body, accelerating the osseointegration process (24).

Surface modification using both sandblasting and acid etch (SLA) creates greater porosity which provides a greater integration between the implant and bone

(24).

Coating the implants surface with calcium and phosphate establishes a strong and direct hydroxyapatite bond between the bone and the implant. Additionally, plasma- sprayed coating is another surface treatment process where a layer of 40-50 micrometers is formed by pulverizing powdered titanium plasma at high temperatures. Resorption of the hydroxyapatite surface, deterioration of the surfaces, lack of homogeneity on the coated surfaces, lack of homogeneity in the composition of the coating products, the weakening of the adhesive properties of the coating surfaces in time and possible microbial contamination are disadvantages of implant coating (24).

Other coating materials include composite, titanium nitrate, carbon, glass, ceramic, and titanium dioxide (25).

Anodic oxidation, an electrochemical process, thickens the titanium oxide layer, enhancing surface porosity, bioavailability, and the osseointegration process. (29).

The application of fluoride onto the implant's titanium surface creates titanium fluoride which increases the differentiation of the osteoblasts and boosts the osseointegration process (30).

Other modifications done on the implant surface to boost osseointegration include creating porosities by laser application, spraying ions onto the surface, application of bisphosphonates and statin in order to decrease resorption and increase the bone density, application of antibiotics to reduce the bacterial activity and the application of growth factor (24).

The figure 2.1. below shows the images of five different surface modifications applied on titanium surfaces, observed under electron microscope with a resolution of 5 microns.

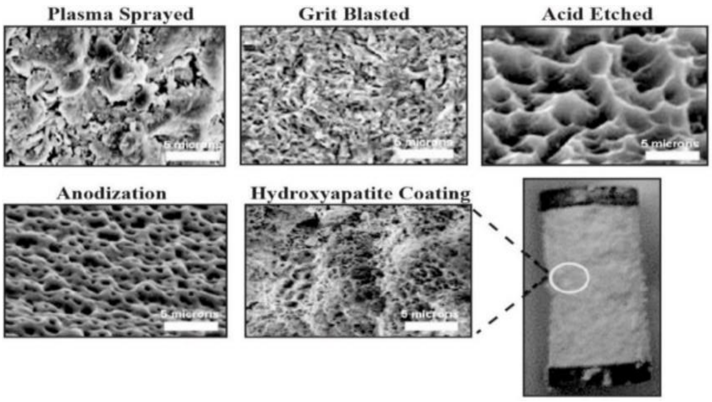


*Figure 2.1. Five Different Titanium Implant Surface Modifications*

Surface modifications used on implants can be classified into three groups (101):

### 2.3.1. Physical (& Subtractive) Surface Treatment

- Machining: The machined implant undergoes turning, milling, or polishing processes, resulting in a slightly rough surface with a surface area roughness ($S_a$) value ranging from 0.3 to 1.0 µm (63).
- Sandblasting: The sandblasted implant undergoes grit blasting with small particles such as alumina or titanium oxide, resulting in the creation of craters and ridges upon impact (63).
- Laser Etching: Laser-etched implants utilize lasers as micromachining tools to achieve selective modifications and generate complex microstructures at both the micrometer and nanometer levels (122).
- Nanoparticle Compaction: The process of compacting nanoparticles onto the implant surface maintains the chemical composition of the surface underneath while changing or adjusting the chemistry and structure of the outermost surface layer. (122).
- Porous Tantalum Trabecular Metal: The titanium alloy and the porous tantalum trabecular metal components of the implant are prepared independently. A porous vitreous carbon scaffold is then applied as a second layer onto the titanium implants. The porous layer, designed with a structure resembling trabecular bone, enhances the bond between osseous tissue and dental implants by promoting osseointegration (123).

### 2.3.2. Chemical (& Additive) Surface Treatment

- Acid Etched: To enhance the implant surface further, particles are blasted onto the implants before acid etching. This sequential etching process removes embedded particles from blasting and creates a dual surface roughness, typically with a $S_a$ value of 1-2 µm (124).
- Alkaline Treatment: Can be achieved by first soaking the implant in high alkaline solutions, followed by heat treatment. Prior to the alkaline treatment, acid etching can be applied to increase the porosity of the titanium surface, enhancing the effectiveness of the subsequent alkaline treatment (125).
- Anodized: The implant undergoes an anodic oxidation process, an

electrochemical procedure conducted in an electrolyte. This results in the creation of a microstructured surface with micrometer-sized open pores (126).

- Peroxidation: Treatment with a peroxide-based chemical agent leads to producing a titania gel layer on implant surface, which helps deposition of apatite. This chemical process involves the chemical dissolution and oxidation of the titanium surface through treatment with hydrogen peroxide (127).
- Fluoride Modified: This process increases surface area roughness by blasting with titanium oxide ($TiO_2$) and treating with dilute hydrofluoric acid subsequently (128).
- Vacuum Treatment: It can be accomplished by exposing the titanium surface to a glow-discharge of energetic ions, which selectively modify the surface properties through bombardment (129).
- Plasma Coated: Plasma sprayed calcium phosphate-coated implants show enhanced bioactivity. One generic form of calcium phosphate coating is hydroxyapatite (HA). Plasma spraying with HA can augment the surface area and increase the average surface roughness (130).

### 2.3.3. Biological/Biomimetic Surface Treatment

- Bioactive Coating: The bioactive coating of titanium implants entails the precipitation of calcium phosphate apatite crystals onto the titanium surface (131).
- Peptide Attachment: This process includes coating the surface of titanium implants with synthetic arginylglycylaspartic acid (RGD) peptides that feature binding sites for integrin receptors (132).
- Antibiotics Attachment: Antibiotics like cephalothin, carbenicillin, amoxicillin, cefamandol, tobramycin, gentamicin, and vancomycin have the capability to bind calcium-based coatings on implants and can be released from these coatings (133).
- Growth Factor Attachment: The surface of the implant can be coated with agents that stimulate osteogenesis, promoting accelerated angiogenesis and bone formation around the implants. (134).
- Bone Remodeling Agent Attachment: The surface of the implant can also be

coated with bone remodeling-associated agents such as bisphosphonates (135).

### 2.4 Osseointegration

Osseointegration, first identified by Per-Ingvar Brånemark at the Goteborg University in 1969, refers to the direct bond observed under the microscope between vital bone tissue and a weight-bearing implant. This seminal definition highlights the structural connection crucial for implant success (31,32,). In 1986, the American Academy of Implant Dentistry expanded on this concept, defining osseointegration as a continuous relationship between bone tissue and the implant body. This dynamic relationship stimulates bone remodeling, ensuring the implant remains securely integrated with the surrounding bone (32,33). Alternatively, Zarb and Alberktsson provided a clinical perspective, defining osseointegration as the establishment of firm fixation during functional loading of an asymptomatic alloplastic material onto the alveolar bone. This definition highlights the practical aspect of osseointegration in ensuring stable and symptom-free implant function (10).

The process of healing in a dental implant resembles that of primary bone healing. The bone surrounding the implant body develops in an open mechanism, which is thought to be the same as the bone development in intramembranous ossification (12,62). This course of action starts with the blood between the implant and the bone which then turns into a blood clot (33). The primary inflammatory response enables mesenchymal stem cells and osteoblastic precursors to accumulate chemotactically on the implant-osteotomy site and secrete osteoids as proteins. As osteoids are produced, they are remodeled into lamellar bone (62). The adhesive proteins which play a role in the cell adhesion mechanism are said to work on the osseointegration process (12). As a result of osseointegration, a few millimeters of cortical bone is produced on the implant body. Once the implant-supported prosthetic is in function, the bone remodeling process begins, and the Haversian bone becomes denser and homogenous (33).

During the placement of the dental implant, the implant-osteotomy site is created around the implant body. However, this site initially consists of non-vital bone, replaced by woven bone characterized by its disorganized structure and limited load-bearing capacity. Over time, the woven bone is gradually replaced by lamellar bone, which is organized and better equipped to withstand loads (36).

Within 6-12 weeks post-implant placement, the crestal portion of the implant becomes enveloped by bone that exhibits increased resilience to functional stress. This enhanced bone density enables it to withstand greater loads and pressure, contributing to the long-term stability and success of the implant (37).

The cornerstone of successful osseointegration in dental implants lies in their stability (32). This stability is theoretically determined by two distinct factors: primary stability, established during the surgical implant placement, and secondary stability, which develops over the course of the healing process (32).

Primary stability hinges on several factors, including the quality and quantity of bone, the design of the implant, and the precision of placement (38,39). Dental implants that can be manually drilled often exhibit superior primary stability due to their increased surface area for bone-implant contact and reduced tissue trauma associated with drilling (39). It is worth noting that primary and secondary stability are not always directly correlated, highlighting the complexity of the osseointegration process (32). This underscores the importance of considering multiple factors when assessing implant stability and predicting long-term success.

Histomorphometric assessment of peri-implant bone remodeling captured using a point count method is shown in Figure 2.2. below. The region of interest was delineated as a 200-micrometer-wide zone aligned parallel to the implant surface (indicated with the black line). Points falling on host bone and newly formed primary bone were annotated in blue, whereas those on remodeled secondary bone were denoted in red (102).

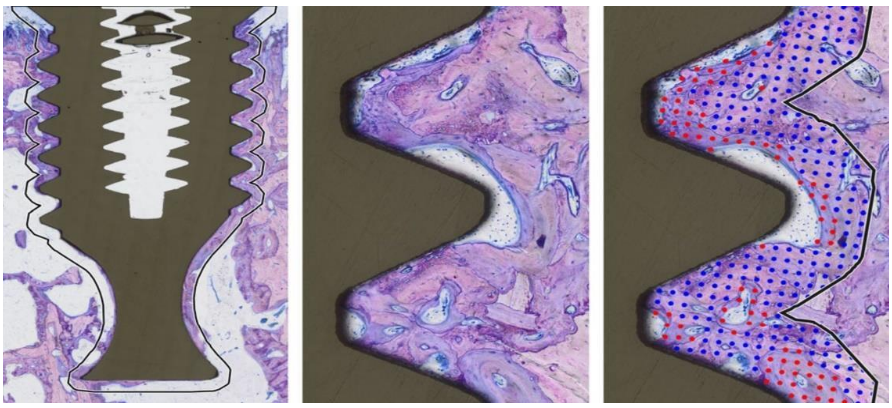

*Figure 2.2. Histomorphometric Evaluation of Peri-Implant Bone Remodeling*

## 2.5 Bone Types

Bone density serves a crucial role in determining the primary stability of dental implants. Lekholm and Zarb's classification system is frequently employed to categorize bone types (28). According to their classification:

Type 1 Bone: Dense, homogenous compact bone

Type 2 Bone: Thick compact bone surrounding dense cancellous bone

Type 3 Bone: Thin compact bone surrounding dense cancellous bone

Type 4 Bone: Thin compact bone surrounding sparse cancellous bone

Bone density not only impacts implant stability but also influences treatment outcomes and the long-term success of implants (32). Therefore, understanding the bone density classification is essential for clinicians in planning and executing implant procedures effectively.

Figure 2.3 below depicts the types of bone structures ranging from I to IV. Starting from Type I to Type IV bone, there is a progressive decrease in cortical bone thickness accompanied by an increase in the ratio of trabecular bone volume. Only a thin cortical bone surrounds the trabecular bone in Type IV.

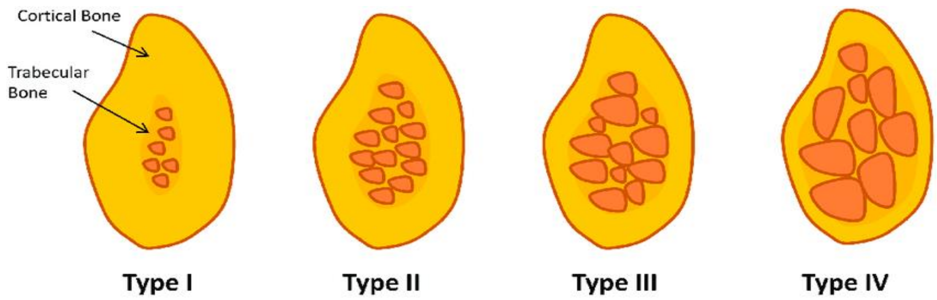


*Figure 2.3. Bone Types according to Zarb et al.*

## 2.6 Implant Components

The primary structure in an implant complex typically comprises two main components: the implant body and the abutment. The implant body remains embedded within the bone, offering substantial support to the overall complex, while the abutment facilitates the attachment of prosthetic restorations. Alternatively, these two components can be integrated into a single unit. Dental implants with two components necessitate a two-stage surgical procedure following the osseointegration phase. However, to either eliminate the need for a secondary surgical intervention or enable a one-stage approach, implant body designs have been developed with a permucosal section (36).

The dental implant body typically consists of a crest module and an apex, offering versatility in sizes, shapes, and macro designs to accommodate various anatomical, aesthetic, and mechanical needs. These implants are manufactured in a wide array of configurations to cater to diverse patient requirements. The grooves on the implant body vary in dimension and design, serving to augment surface area and enhance mechanical retention, thereby promoting successful integration with the surrounding bone (36).

A two-piece dental implant body consists of a crest module which links the prosthetic restoration to the implant body. This portion of the implant complex allows the formation of the transition zone, which is the load bearing area of the implant body. During osseointegration, the crestal bone is resorbed which leads to the appearance of the crest module. Bacteria plaque can accumulate in this region. Therefore, the crest module designs are flat and smooth. The portion of the crest module which connects to the abutment consists of a platform which impedes the axial forces. Moreover, this platform can contain a nonrotational component which can extend both towards the implant body (internal hexagon, morse taper, internal arrow) and outwards (external hexagon) as all of those serve only to mate the two components together precisely (36).

After surgically placing the implant, a cover screw is used to cover the opening of the implant body. This prevents the collection of food debris, migration of bone tissue and gingival tissue into the implant body during osseointegration. In two-stage implant procedures, after the osseointegration process, a healing cap is placed in order to scaffold the surrounding soft tissue and enable its proper formation around the implant. In a one- stage implant procedure however, a healing cover is directly placed or a supra gingivally extended implant body can be used (36).

A temporary prosthetic restoration can be used after a two-stage implant procedure. It can be beneficial in anterior portions with high esthetical expectations, prevent from external forces during osseointegration and in cases where the bone quality is poor. For a single stage implant procedure its advantageous as it removes the requirement of a secondary surgery, disables the formation of a micro gap, and decreases the fulcrum distance between the contact and force area (55).

The abutment, a crucial component of the implant system, serves as the support structure for the prosthetic restoration. The connection between the abutment and the prosthetic component is facilitated by one of three distinct systems (36). In some cases, the prosthetic component is affixed to the abutment using a screw, while in others, it is cemented in place. Alternatively, in instances where the prosthetic restoration is removable, the abutment functions as an attachment point to secure its retention.

Implant abutments can be classified based on several factors, including the connection type of implant-abutment, abutment material, retention mechanism with the prosthesis, and fabrication method.

### 2.7 Implant-Abutment Interface

The interface between the implant and the abutment can take two forms: internal or external. External connections typically feature hexagonal or octagonal shapes and may include spiral flutes. On the other hand, internal connections commonly utilize morse taper, hexagonal, or octagonal interfaces (14). Furthermore, variations in internal connections may include octagonal, tapered, cylindrical hexagon, grooved, or pinned configurations (36).

#### 2.7.1. External Connection

The external anti-rotational connection type was first introduced by Brånemark and is one of the most popularly used connection types. They were primarily invented for the sole purpose of being easily manipulated. The external hexagonal system can be used in two-stage implant surgeries as they consist of an anti-rotational mechanism, can be easily retrieved, and simplifies the impression and the prosthetic phase due to its compatibility and adjustability with different prosthetic solutions (40). Nevertheless, it also comes with several drawbacks, including limited extent of contact between the restoration and the hexagonal part of the implant head, potential rotation between the platform and the internal hexagon of the restoration, and elevated tension in the screw connection. There's speculation that under significant occlusal loads, the external hexagon could permit micromovements of the abutment, leading to joint instability and possibly resulting in abutment screw loosening or fatigue fractures (112,113). The flat external connection type is more likely to receive bending forces and transfer the forces onto the implant body. Several implant abutment systems have a gap on the connection area and the fulcrum point is far when the lateral forces are applied (55). Research findings have indicated that the loosening rate for this connection type varies from 6% to 48% (114). When the external hexagonal implants are placed as a single tooth, screw loosening rate is expected to be increased. The reasons behind this could either be due to the excess vertical forces, lateral forces exerted on the non-functional area and the mismatch of the prosthetic component. In order to prevent such an event, a gold-plated abutment can be used, as these galvanized pure gold abutments can increase the resistance to friction forces and preload pressure (42).

#### 2.7.1.1. Tapered External Hexagon

By implementing a tapered interface, the hexagonal mating surfaces intricately interlock, establishing a frictional engagement to enhance precision during the transfer process and augment stability during function (115).

#### 2.7.1.2. External Hexagon

This external implant abutment interface features an eight-sided configuration, permitting a 45° rotation of the abutment. Due to its octagonal shape resembling a circular form, it exhibits minimal resistance to rotation, thereby resulting in its relatively limited popularity as a design choice.

#### 2.7.1.3. Spline Connection

Splines represent fin-to-groove anti-rotational configurations with a longstanding and proven track record in engineering. Originating from Calcitek in 1992, this design comprises six spline teeth extending outward from the implant body, precisely interlocking with the six corresponding grooves on the abutment. This configuration significantly reduces the occurrence of screw loosening and minimizes rotational movement in contrast to traditional external designs (116).

### 2.7.2. Internal Connection

The internal hexagonal system involves the hexagon and the screw extending into the implant body, enhancing stability of the prosthetic component. This connection type developed from the external hexagon, aiming to improve load absorption under lateral forces and thereby reduce mechanical and biological complications like screw loosening, fractures, and marginal bone loss. The greater depth of connection within the fixture body enables more uniform dissipation of mechanical stress, spreading it across the implant wall and consequently to the surrounding bone throughout the implant rather than just at the crestal level (70). This ability is achieved by the hexagonal socket shape on the prosthetic component and by the increase in depth of the internal hexagonal connection which allows the transfer of the fulcrum point to the middle third of the implant-prosthetic complex (42). The internal hexagonal systems can transfer stress more equally, allow greater stability and are more resistant to lateral forces. The internal taper type allows for a better adaptation between the different components and prevents from screw-loosening (40,41,42). The internal tapered systems transfer the forces toward the connection's internal slope (55). The internal connections can be used in one-stage implant surgeries, single-tooth implant applications and in cases of decreased interocclusal distance (40,42).

#### 2.7.2.1. Six-Point Internal Hexagon

The most prevalent commercially available connection type is characterized by a hexagonal geometry, enabling the abutment to align with the implant fixture at 60° angulation, thereby allowing six distinct positions. This design has demonstrated efficacy in distributing forces deeply within the implant, consequently enhancing joint stability (115).

#### 2.7.2.2. Twelve-Point Hexagon

Numerous manufacturers also offer the 12-point hexagon design, which provides increased versatility for abutment placement over the fixture. This design permits abutment positioning on the implant at 30° intervals. An investigation by Tang et al. demonstrated that a 12-point double hexagon connection exhibited superior stress distribution and resulted in reduced displacement when compared to alternative designs (117).

#### 2.7.2.3. Three-Point Internal Tripod

This connection features a triangular internal geometry with a tri-channel design. Its primary drawback is that it permits abutment positioning on the fixture only at 120° intervals. Consequently, it is not a highly favored design due to its limited options for placement.

#### 2.7.2.4. Internal Octagon

This connection is characterized by an eight-sided internal geometry, enabling the placement of the abutment at 45° intervals. Due to its geometric resemblance to a circle, it provides minimal resistance to both rotational and lateral forces during function (116).

#### 2.7.2.5. Morse Taper Connection

Screwless morse taper systems differ from other systems in that when torque is applied, it is received as a friction force by the tapered area on the abutment which leans onto the internal wall of the implant (41,42). In this way, a connection is established between the internal wall of the implant and the outer wall of the implant abutment (41). Additionally, the morse tapered systems provide a longer clinical success rate as the implant-abutment connection is placed in the intrasulcular region. The screw retained morse tapered connection types are more resistant to stress than external hexagonal systems. This is due to the fact that their connection joint is lodged deeper, and they have an angle of 8-11 degrees convergent internal wall. The implant's inner wall provides support for the abutment, reducing stress on the implant body. Due to this reason, the torque required to loosen this type of connection is 30 percent more than the torque needed for its stabilization (42). The main definition of the morse taper system is that their connection is tightened as an adaptational result to the friction between the surfaces. However, other authors define this connection as a cold fusion. Therefore, the force exerted for loosening the abutment is greater than the torque required to initially tighten it (41). This connection type also increases the resistance of the abutment against bending forces. Additionally, morse taper systems allow the formation of the gingival tissue around implant abutment (42,43).

Introduced by Bicon implants, the first design features a true Morse taper with a taper angle of 1.5°. The initial adoption of 8° design occurred within the ITI group in Switzerland. The rationale behind this design is to create a tapered connection that provides mechanical stability, reliability, and a self-locking interface. To enable rotational adjustment of the abutment over the implant fixture at various angles, Wiskott and Belser enhanced the original Morse connection by incorporating an internal hexagon in the center of the Morse taper connection. The 11.5° abutment marketed by Astratech features a conical seal design aimed at sealing the connection, thereby reducing micromovements and minimizing microleakage at the implant-abutment interface (118).

Mechanical complications are less common in morse taper systems (73). The design of the morse taper system consists of a micro-gap between the implant and the abutment which decreases the crest bone loss (43). Due to its fragile design, rough prosthetic components can easily disrupt the system. The implant must be placed without any angles so that the abutment is placed on it axially (42).

Below Figure 2.4. shows three different implant-abutment connections and types of their interface as cone morse, internal hexagon, and internal hexagon. Three different abutment variations for each prosthetic interface are provided. Given variations for each interface are multi-unit abutment, UCLA abutment, and solid abutment respectively.

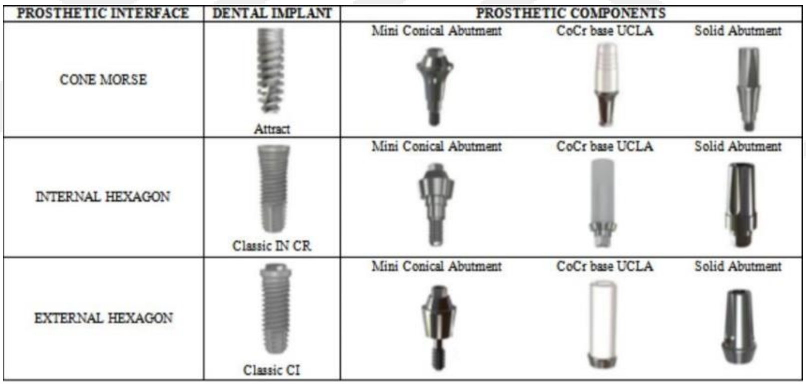

*Figure 2.4. Implant-Abutment Connections (34)*

### 2.7.3. Platform Switching

Platform switching systems are used with the intention to decrease and control the bone loss around the implant. To do so, the prosthetic component placed on the implant must have a diameter that is less than that of the implant. This system decreases reduction in bone volume within the initial year post-implant surgery as it conducts and disperses the forces received by the implant. The platform switching system is also used as a soft tissue barrier disabling the bacterial accumulation and thereby decreasing the crestal bone loss. This system decreases bone loss around 1.56 ± 0.7mm. It provides a more aesthetically pleasing result, has a great implant-bone interface, increases the primary stability and clinically it protects soft tissues such as the interdental papilla. Platform switching systems can also be used in areas with decreased mesiodistal distances (42,43,44).

**2.8. Implant Size**

The forces conducted within the implant-bone depend on the type of force applied, the characteristics of the materials used in the implant and prosthetic component, the length of the implant, the geometry and width of the implant, the composition of the implant's surface, the implant-bone connection type and the bone's quality and quantity. The main factors which affect the conduction of forces between the implant and bone are the length, diameter, body, and flutes shape. The implant's size and shape does not affect the success on type 1 and type 2 bones as their structure can handle most implants. Whereas for bone types 3 and 4, implants of a greater diameter and longer ones are preferred for a successful outcome (15).

Increasing the length of the implant increases the chances of primary stabilization and the area between the implant and bone. Nevertheless, after placing the abutment on a longer implant, it also provides resistance against torque and shear forces (36).

The implant's diameter is just as important as the implant's length, and it is required to use an implant with a greater diameter in order to decrease the stress acting upon the system. The implant's surface area is affected by the number and the depth of the grooves on the implant body. This is why it is important to consider the patient's needs when selecting the adequate implant design (36).

The implants diameter directly affects the negative stress acting on the bone around the implant's crest. Therefore, an increase in the implant's diameter decreases the stress acting upon the cortical bone. The alterations on the length of the implant affect the cancellous bone as it is the bone that surrounds the implant's body (45). The cortical bone bears the load from the crest module region of the implant. Whereas the cancellous bone receives the stress from the implant's apex and from its thread. The distribution of stress is also affected by depth and width of the implant (15).

The depth of the implant significantly influences the primary stability established within the cortical and cancellous bone. In contrast, the angle of the grooves and the spacing between the threads do not have a significant impact on primary stability in compact bone. Increasing the distance between threads, however, results in a larger surface area for the implant, positively affecting stress distribution. Consequently, individuals with low-quality bone, subjected to strong occlusal forces, and those in need of shorter implants may find greater benefit from implants featuring a higher number of threads.

The diameter selection of the implant should be based on the depth and width of the bone, the patient's occlusion, emergence profile and the patient's edentulous areas. Implants with larger diameters are used on the posterior region in cases where the vertical bone is insufficient, the failure of osseointegration and mechanical attachment, to modify the emergence profile and to distribute stress to a greater area (55).

The implant's design affects the type and amount of force acting on the implant- bone interface (36). There are three forces acting on the implant-bone interface: shear forces, compressive forces, and tensile forces. The shape of the implant and the area in which it's placed dictates the type of force to arise (15). Implants come in trapezium, tapered, flat, oval, and threaded shapes. Clinically, there are no facts favoring a specific implant shape, nonetheless, tapered implants are the preferential ones. The tapered implants have less bone perforation incidences and they easily distribute the stress on the implant-bone interface (15,46).

**2.9. Stress**

Stress, defined as the force exerted across a unit area in a functional context, is a critical factor impacting every stage of an implant procedure (36). As a result, it is imperative to examine the effects of stress before delving into potential complications arising from it.

The stress induced by the implant or prosthetic component can give rise to various complications during both surgical and prosthetic phases. Some of the complications associated with stress on implants include:

- Early crestal bone loss
- Implant failure
- Bone loss due to excessive occlusal load
- Screw-loosening
- Implant and/or Prosthesis fracture

The stress and forces acting on the bone affect the remodeling process around the dental implant. Excessive stress on the implant-bone interface can lead to severe bone loss. When stress and force applied exceeds the physiological norm, it can cause micro fractures on the bone, decrease blood flow and cause resorption due to excess pathological load (36). Early crestal bone loss around the osseointegrated implant could mean the loss of the bone under the mucosa around that implant within 10 years. This can start as marginal bone loss and end with a total bone loss around the implant. There are several studies and different views on marginal bone loss (36). The reduction in bone volume surrounding the implant in the first year is generally 0.9 mm and around 0.1 mm in the following years (47). The marginal bone loss around the implant has "U" or "V" shape. Some of the reasons for early crestal bone loss are:

- Removal of the periosteum during surgery
- Implant osteotomy
- Micro-gap between the implant and the abutment
- Micro-movements between the abutment connectors
- Microorganisms
- The formation of a biological gap
- Stress (36)

Early implant failures are a complication caused by the second stage of the implant surgery (36). Crestal bone loss and implant failures are more common on sparse bone tissues rather than denser bone tissues (48).

The quality of bone affects the area that receives stress. In dense bone, the area of stress is in the crestal region, whereas in sparse bone the stress is more in the apical region. Due to this fact, bone loss in the crestal region is seen in sparse bone and its form on the largest part of implant's body (36). Nevertheless, the stress conducted from the dental implant onto the crestal region is greater on type 4 bone than in type 1 (49).

There is a direct relationship between the bone density and the implant-bone interface. In D1 bone, the implant-bone interface is the greatest whereas in D4 type bone is the least. Therefore, in less dense bone tissues a larger surface area for supporting the dental implant should be created (36). In order to decrease the stress received by the implant system, the stress can be distributed on a larger surface area.

A larger surface area of the implant system can be created by increasing the number of implants and decreasing the number of pontics on the dental bridges (36,50). However, these methods are suitable for patients with higher risk factors due to occlusal forces rather than patients with ideal occlusal forces. Having a greater number of implants also lowers the likelihood of implant fractures. Adding more splinted abutments improves the retention of the prosthesis and reduces the stress on the system. (36).

The force can be altered by the amount, time, direction, and the leverage factors applied. Therefore, the treatment plan is an important factor to consider when lowering the stress (36).

### 2.10. Complications in Dental Implant Applications

While dental implants offer numerous benefits in addressing tooth loss, their widespread adoption has also led to an increase in both surgical and mechanical complications. These complications can be broadly categorized into three main types: biological, mechanical, and aesthetic (51).

#### 2.10.1. Biological Complications

Biological complications encompass issues related to the interaction between the implant and surrounding biological tissues. Common complications in implantology include mucositis, peri-implantitis, fistula formation, soft tissue hyperplasia, and implant loss (51).

The oral cavity serves as an ideal environment for microbial colonization, facilitated by the presence of saliva. Biofilm formation occurs on natural teeth as well as any artificial surfaces introduced into the oral cavity. Certain anatomical features, such as periodontal pockets, tonsils, and folds of the tongue, create favorable ecological niches that support the growth and proliferation of bacteria (79).

Biofilm serves as the primary causative factor underlying periodontal diseases, including gingivitis and periodontitis, which can progress to mucositis and ultimately develop into peri-implantitis (80).

Peri-implant diseases encompass infectious conditions categorized as peri-implant mucositis and peri-implantitis. Mucositis manifests as an inflammatory lesion in the soft tissue surrounding the implant, while peri-implantitis involves bone loss and compromises implant stability (81).

These diseases often present asymptomatically in the peri-implant area, making early detection challenging. However, if left untreated, they can contribute to implant failures and subsequent loss (82).

#### 2.10.2. Mechanical Complications

Excessive forces affecting the implant prosthesis do not create occlusal trauma since osseointegrated implants lack a periodontal ligament, instead a complication would occur on the mechanical structure of the implant (52). Factors that are in relation with the mechanical complications are excessive forces, narrower implants, inadequate number of implants supporting the prosthesis, material choice of the implant abutment screw and the use of cantilever (53). Excessive loading is caused by forces applied other than implants vertical axis, increased crown-root ratio, parafunction, overuse of cantilevers, sharp angulation of implant abutments (51). As mechanical complications lower the life quality of the patient, they also cause the patient both time and money loss (54).

Dudic and Mericske-Stern have categorized the prosthetic complications about implant restorations as the following: (54)

- Complications and failures in implant related parts

(abutment, bar, stabilizer, occlusal screw)

- Mechanical and structural failure in prosthesis

(prosthetic design, denture base, teeth, making of a new prosthesis)

- Prosthesis redesign

(lining, occlusion, aesthetic, hyperplasia)

##### 2.10.2.1. Screw Loosening and Fracture

Abutment screw loosening or fracture ranks among the most prevalent mechanical complications associated with dental implants (51). Implant abutments and prosthetic screws are particularly prone to loosening under certain conditions, such as parafunctional habits, single-tooth restorations, or cantilever designs (38, 64). Studies have indicated that the rates of abutment screw loosening range from 5.8% to 12.7% after a 5-year follow-up period (1).

Several factors contribute to the occurrence of screw loosening, including:

- insufficient tightening torque.
- excess mechanical forces.
- noncompatible abutment design and material.
- vibrations during functional loading.
- change in temperature in the oral cavity.
- malposition of the implant. (51,55,64)

The occurrence of screw loosening in dental implants is influenced by numerous factors, including metallurgical properties, implant design, and the number of splines on the implant body (36). Additionally, the use of angled abutments can concentrate forces along the implant's long axis, potentially leading to screw loosening and fractures (65).

Occlusal forces acting on dental implants generate an overturning moment that can result in screw loosening, crestal bone loss, and even implant body fractures (36).

The consequences of screw loosening extend beyond mechanical issues and can have significant clinical implications. These include:

- Fracture of the implant and screw.
- Uneven distribution of occlusal forces.
- Formation of micro-gaps between the implant and abutment due to micro-movements, leading to bacteria accumulation.
- Risk of peri-implantitis and loss of osseointegration (55, 64, 66).

According to Bickford, screw loosening is a two-step procedure. First, the effect of the external functional forces causes a decrease in the tightening torque. Vibrations and micro movements loosen the screw, reducing the optimal preload. Secondly, the preload is reduced to a critical level, leading to the rotation of the splines and ultimately the function loss of the screw joint (67). The screw loosening creates metal fatigue which later leads to screw fracture (52).

Additionally, screw loosening creates a great stress on the alveolar bone during immediate loading, which can disrupt osseointegration (68).

There are two methods devised prevent implant-screw loosening; one of which is the screw joints preload pressure, and the other is the anti-rotational element (69). The implant body's anti-rotational component height affects the amount of force exerted on the abutment (36). The rotational maladjustment between the implant and the abutment can lead to the failure of the screw joint. Nevertheless, in external hexagonal systems, its height plays a vital role in anti-rotational stability (69). As the hexagonal height increases, the forces acting on the screw decreases (36). Therefore, an anti-rotational system appropriate to the patient's requirements must be chosen.

In an effort to achieve precise preload on the abutment, it is necessary to perform a second tightening shortly after the initial torque application. This additional tightening is crucial to counteract any loosening that may occur as a result of the initial tightening process (36).

Another way to prevent screw loosening is by creating a passive adjustment of the prosthetic component (51). In order to provide a passive adjustment, the prosthetic components can be manufactured using a CAD/CAM (computer-aided design/ computer- aided manufacture) and benefit the use of laser technology. Moreover, a good conventional impression material with using the right technique would provide a passive component. Nevertheless, occlusal adjustments and choosing the appropriate implant system should also be considered (51).

Due to the spread of the single implant prosthetic component use, several ways which prevent their rotation have been brought forward. For instance, changing the type of the material, enhancing the sensitivity of the hexagon, and altering the implant-abutment interface (42).

Abutment fracture is a less common complication. With metal abutments, the fractures occur on the screw whereas with ceramic abutments, the fracture occurs on the abutment itself. Unfavorable occlusal forces, ill-matched abutment-prosthetic component and a wrong choice of prosthetic component can cause this type of complication (51,71).

On the other hand, implant fracture is the least seen complications with a 1% chance of occurrence. This kind of complication takes place if the implant location, width, and length are inappropriate. Also, the excessive occlusal forces, the compatibility, the design of the prosthetic component and the loss of crestal bone are other factors which could cause an implant fracture (51,72).

**2.10.2.2. Complications Occurred in Prosthesis Materials**

Veneering ceramic fracture of implant supported porcelain fused metal restorations and acrylic resin fracture of hybrid restorations are complications that occur frequently, and main reasons are improper preparation of metal framework and occlusion as well as problems encountered in laboratory steps (51,85,86). Metal framework should be thick and hard enough according to the chosen compound and occlusal forces. Moreover, problems with the metal-ceramic bonding might lead to fractures in those materials. On the other hand, fractures that happen in metal framework are seen mostly in soldering spots and cantilever connections. In order to eliminate these consequences height, thickness, alloy type, alloy quality, design and passive fit of the metal substructure should be carried on accordingly (51). Loss of retention or decementation of an implant supported fixed dental prosthesis is a complication that is related to unnecessarily short abutments and incorrectly selected abutments (87,88).

It is reported that implant supported removable prosthesis requires maintenance more often and has an increased complication rate. Fractures in the prosthesis material, artificial teeth falling out from the base and need for relining and rebasing due to distortions in implant-tissue borders are the complications encountered with implant supported removable prosthesis (51,53). It is seen that those associated complications tend to occur more frequently in the maxillary jaw rather than the mandibular jaw.

In order to prevent complications, there are crucial points with implant supported removable dentures such as proper material selection, having adequate material thickness and choosing the attachment type according to the distance between two jaws (51).

**2.10.2.3. Aesthetic Complications**

In modern day dentistry the implant survival rates can be relatively predicted and thus implant dentistry has redirected its attention toward aesthetic success. Restoring missing anterior teeth especially in the maxillary jaw can be particularly challenging for the teeth are in a highly aesthetic area which presents anatomical defiance when placing implant (75).

Determining the frequency of implant failures is challenging due to aesthetic reasons because most studies on implant success still do not provide aesthetic success criteria. Some literature reviews that have addressed aesthetic complications suggest that the failure rates due to aesthetic concerns in single implant crowns within the anterior maxilla range from 4% to 16% (76-77).

The most common reported aesthetic complication is gingival recession that leads to exposition of the implant and abutment junction. In addition to that, there is a study reporting that up to 61% of the studied cases have at least 1 mm of gingival recession on their facial aspect (78). Additionally, poorly selected shade for the prosthesis and the absence of interdental papillae also accounted to common implant aesthetic failures.

To mitigate potential complications, it is essential to adopt a comprehensive approach by evaluating all tissues collectively during the planning phase of implant treatment. A majority of aesthetic complications can be preemptively addressed through thorough presurgical planning and corrective measures before the actual implant surgery. This entails a meticulous examination of factors such as available bone tissue, soft tissue characteristics, tissue biotype, considerations for delayed versus immediate implant placement, optimal implant selection, the number of teeth requiring replacement, and other available treatment alternatives (75).

### 2.11. Occlusal Forces

It is reported that the maximum biting forces are between 200N-240N, and the lateral component of those applied forces are 20N (74). It is assumed that a dental implant can withstand nonaxial forces up to 500N (83).

Different biological problems will occur when loading natural teeth and dental implants due to their different anchorages. While axial forces should be preferred for dental implants, they are prone to receive oblique forces more. In the clinic, forces that disturb the implant screw joint are generated from centric, eccentric, and irregular forces. Interproximal and cantilever contacts along with poor prosthesis fit also cause the implant screw to destabilize (42).

In implant applications, occlusal evaluation of an implant supported prosthesis bears a significant role in the distribution of occlusal forces. When treating single teeth with dental implants, tripod contacts should be carried on, occlusal table should be narrowed, and cusp inclines should be less steep. In partial edentulous cases, group function or canine guided occlusion is supposed to be selected according to the type of edentulousness. Bilateral balanced occlusion ought to be favored when treating edentulous patients with dental implants (84).

Bruxism, clenching, using cantilevers, premature contact in prosthesis, smoking, implant positioning in dental arch are risk factors for dental implant treatment. In bruxism, increased amount of applied force and cycle counts cause additional metal fatigue in the implant material. In order to enhance the lifespan of implant treatment, implant count can be increased, any occlusal irregularities should be corrected and with patients who are also being treated with occlusal splint, the areas in contact with implant supported teeth and the occlusal splint can be relieved. Elimination of lateral contacts of restorations located in the posterior area decreases the negative outcome of bruxism (36).

Cantilevers of 15 mm in mandibular jaw and 12 mm in maxillary jaw causes failures in dental implant treatment. It is known that premature contacts also cause failure. Studies reported that on human trials a premature contact height of 100 μm caused complications in dental implants (79).

**2.12. Mechanics of an Implant Abutment Screw**

The screw features a helical thread that, upon rotation, moves it vertically within the implant either upward or downward, depending on the direction of rotation. McGlumphy et al. defines the screw joint as a unit of two parts which are tightened together by a screw, like as an implant abutment and implant body being held together by an abutment screw (3). Through applying torque, a screw can be tightened. When the torque is applied, it creates a force within the screw which is called preload. Whilst a screw tightens, it elongates, and tension is produced. And then a clamping force is created via elastic recovery of the screw which pulls the 2 parts together (90). The clamping force is of equal magnitude to the preload (3).

In opposition to the clamping force, there is a force that attempts to separate the screw joint, called joint-separating force. When the joint-separating forces working on the screw joint are excessive than the clamping forces fasting the screw unit together, screw loosening happens (3). Overabundant forces lead to movement between threads of the screw and the bore and may result with a loss of preload (91).

Separating forces should be minimized, and it is not essential to eliminate them completely. Reducing separating forces while maximizing clamping forces can effectively prevent unintentional loosening of the screw.

Following figure 2.5. depicts sagittal projection of an implant-abutment complex with morse taper connection showing the internal surfaces of an implant and their relations with implant abutment and abutment screw.

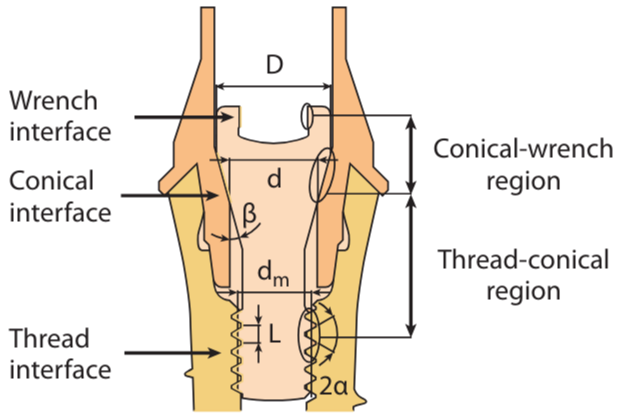


*Figure 2.5 Geometric Parameters of an Implant Complex (35)*

### 2.12.1. Preload

When the clinician tightens the implant components with a screw, torque is transmitted to the screw and that tightening creates a preload within the screw. The settled preload and the applied amount of torque are proportional. The clinician applies the desired amount of torque according to the manufacturer, by either using a preset friction-style implant torque wrench or by deciding through an eye gauge of a spring-style implant torque wrench. Appropriate magnitude of torque values for individual cases can be delivered in repetition with the help of an implant torque wrench (3).

A dental implant assembly comprises multiple components, including an implant body, an abutment, and an abutment screw. Typically, a torque is applied to the connector screw using a torque wrench to securely attach the abutment to the implant body. This tightening action creates an axial tension on the abutment screw surface in contact with the adjacent material, known as preload, which is as shown in

Figure 2.6. When the screw is tightened against a material, the force is distributed throughout the material, resulting in the screw bearing only a fraction of the total load. Meaning when the correct volume of tension is exerted to the abutment screw can hold a considerably higher load (104). The magnitude of preload plays a crucial role in the success of dental implants. The primary reason for the failure of most two-piece dental implants is often attributed to screw loosening (1).

Conversely, an excess of preload can induce wear or harm to the screw threads and potentially result in plastic deformation (106).

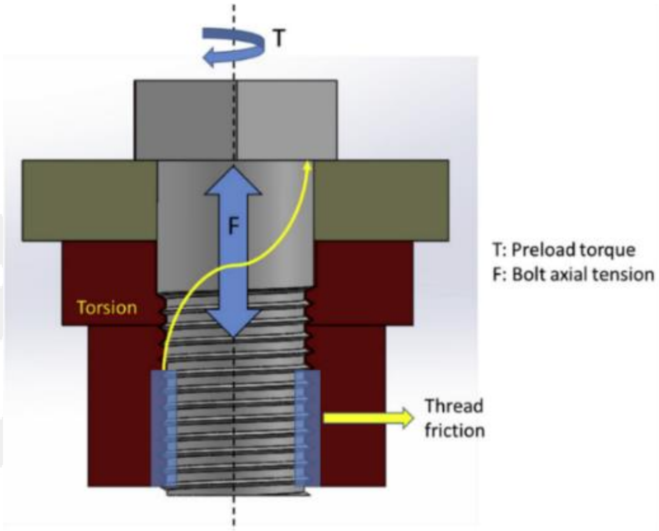


*Figure 2.6. The application of preload on a screw to tighten 2 units*. A tensile force is generated on the surface of the screw after torque application (104).

The applied torque and some factors, such as alloy of the screw, head design of the screw, and surface of the abutment determines the preload (3). The preload primarily depends on the applied torque and, to a lesser extent, on factors such as the material of the components, design of the screw head and threads, and surface roughness. Screw yield strength and the strength of the bone/implant interface restricts the extent of the applied torque (69). Microroughness on the mating surfaces of implant components is an important factor that effects insertion as an implant screw is tightened (66). Irregularities on the milled implant surface become flattened on contact with component surfaces during tightening torque application.

The final preload for the screw joint is weakened by the energy required to straighten irregularities on the surface. Furthermore, even if the tightening torque remains permanent, higher friction decreases the final preload because of tightening energy being lost to frictional resistance (67). With the impact of friction and insertion, preload is no way equal to the tightening torque and can be described with the following formula: (67)

**Equation 1.**

$$T_{in} = F_P[(P/2\pi) + (\mu_t r_t / \cos \beta) + (\mu_n r_n)]$$

Where:

Tin = torque applied to the screw

FP = preload created in the screw

P = pitch of the thread

μt = coefficient of the friction between bore and screw thread

rt = effective contact radius of the thread

ß = half-angle of the thread

μn = coefficient of friction between the face of bore and the upper joint surface

rn = effective radius of contact between the bore and joint surface

The formula above explains the torque applied to the abutment screw is equal to the preload created in the screw multiplied by the rotation of abutment screw and the effect of coefficient frictions of abutment screw parts in relation with the implant-abutment complex. Which translates to the amount of preload will always be lower than the tightening torque applied to the abutment screw because of friction.

Alternatively, preload of the screw can also be calculated by using an indirect measure with reverse torque values (99), using the following formula:

**Equation 2.**

$$Ffs = \pi/P\ (Tfs - |Tfu|)$$

Where:

$Ffs$ = preload

$P$ = thread pitch

$Tfs$ = seating torque

$|Tfu|$ = removal torque.

Preload is determined by both the applied torque and the friction between the abutment screw and implant components (67). When preload is applied to a screw, the connected elements are compressed, and the screw experiences minimal impact as most of the load is absorbed by the components of the implant-abutment junction (94). Friction is influenced by material properties, the presence and type of lubrication, and is quantified by the coefficient of friction (COF). A higher COF results in reduced preload values, while a lower COF leads to increased preload values when using the same tightening torque. In mechanical engineering, it is typically assumed that around 90% of the tightening force is needed to overcome friction—50% for the screw head friction and 40% for the screw threads. Consequently, only 10% of the tightening force generates the preload. To address this, some manufacturers offer screws with treated surfaces to reduce friction, enabling a higher preload to be achieved with the same tightening torque (107).

Sagheb et al. reported that the preload values achieved at a specific tightening torque can exhibit significant variation, and repeated utilization of implant-abutment screws may lead to reduced preload even with consistent tightening torque. (108).

The relationship between torque and preload is not linear and is influenced by multiple factors, with the coefficient of friction being the most impactful. This coefficient depends on various aspects such as the hardness of the threads, the surface finish, the type of lubricant employed, and the speed at which tightening is performed (109). Out of the initial torque applied, only about 10% is converted into preload, while the remaining 90% is utilized to overcome friction between surface irregularities (92). Manufacturers recommend a preload torque ranging from 10 to 35 Ncm, with the specific value dependent on factors such as the material of the screw and the type of the implant-abutment connection (97).

Titanium alloys are primarily limited by their inadequate friction and wear resistance, which is why titanium screws struggle to achieve high preload values

(108). To mitigate the disadvantages of poor friction and wear resistance in titanium alloys, some manufacturers provide carbon-coated screws with a diamond-like carbon surface. Additionally, studies suggest that gold or gold-coated screws, when tightened with the same torque, can attain higher preload values compared to titanium screws (110).

Another important factor resulting in loss of preload is the settling effect, and it is believed that the settling effect can lead to a of loss 2-10% of the initial preload (92,97).

**2.12.2. Joint-Separating Forces**

The screw component in an implant prosthesis is consistently subjected to external forces that can cause separation of the joint. Intraoral separating forces are off-axis occlusal contacts, excursive lateral contacts, interproximal contacts between natural teeth and implant restorations, protrusive contacts, parafunctional forces, and misfitted frameworks. After external forces exceed the preload of screw joint, that joint develops into an unstable unit. The preload gets eroded rapidly by the external load, deriving in vibration and micromovement that further leads to screw loosening. If loosening occurs, the screw joint can be treated as failed since the intended function will cease to perform (91).

The clinician must observe and recognize the possible forces that will act on screw joint which will lead the system to screw loosening or other possible complications and take precautions to minimize or avoid the negative outcomes.

**2.12.3. Settling Effect**

Another significant factor contributing to the loosening of screws in implant-supported restorations is the settling effect, also referred to as embedment relaxation. Embedment relaxation arises from the inherent lack of absolute smoothness on surfaces, playing a pivotal role in the stability of implant screws. Despite meticulous machining of the implant surface, microscopic examination reveals a subtle roughness on the material. This micro-roughness prevents two surfaces from achieving complete contact with each other (92).

Under the pressure of loading, rough surface gets flattened and embedment relaxation happens as the rough spots are the only place that are in contact with each other when initial tightening torque is activated. Micromovement will develop between the surfaces just after the external loads are inflicted upon the implant abutment screw interface. Those two surfaces are brought together by the wearing of the contact areas. It has been reported that the initial preload lost due to embedment relaxation is 2% to 10% (93). Therefore, the torque needed to remove a screw ought to be less than the torque that was used to place the screw in the first place (94).

Friction of the threads at initial tightening and loosening are superior to later tightening and loosening cycles and decays over repetition (95). Some authors have indicated that implant screw joints should be tightened after the initial insertion of screw and periodically from that time forward (90,96,97).

Figure 2.7. shows the sagittal section of an implant-abutment complex tightened and the abutment screw. Discrepancies between the surface of abutment screw threads and the implant interface can be observed.

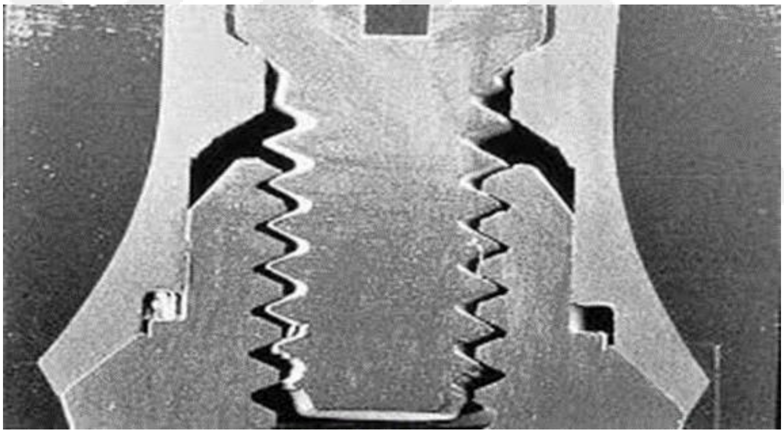

*Figure 2.7. Sagittal Section of an Implant-Abutment Interface*

Sagheb *et al* reported that rough surfaces and high external loads contribute to an increase in the settling effect. The amount of relaxation depends on roughness of the initial surface, hardness of the surface, and magnitude of the loading forces. Volume of embedment relaxation increases with rougher surfaces and larger external loads (95). Increased surface roughness and/or hardness of materials would require more force to smoothen out the discrepancies on material surface, and the lack of precision in material production would lead to a product with increased surface irregularities.

According to Shinohara et al.'s research (98), screws fabricated from grade 4 pure titanium exhibited significantly more loosening compared to screws made of the titanium alloy Ti-6Al-4V. The friction coefficient at the interface between the screw and the implant's internal surface is identified as a key factor influencing the preload value. A lower friction coefficient, achieved with the same settling torque, leads to a higher preload (121).

Park *et al.* evaluated the surface properties of coated or plated screws made of titanium and gold alloy, as well as assessing the physical characteristics of the coated or plated material through scratch tests. They reported that in clinical practice the use of gold-plated screws is recommended to mitigate screw loosening due to reduced settling effect and friction forces during tightening and loosening processes. Additionally, it was reported that teflon coating aids in reducing frictional forces, although it carries a risk of exfoliation (119).

Bakaeen et al have reported that after the prosthetic gold screws were tightened to 10 Ncm following the manufacturer's guideline, the torque value of untightening eventually be 2 to 3 Ncm fewer than the tightening torque of different test groups (96). In addition to that, Sakaguchi and Borgersen also reported that after the first few seconds or minutes of tightening, embedment relaxation resulted in a loss of 2% to 10% in preload (93).

Siamos et al, indicated that increased torque values above 30 Ncm for implant abutment screws can be advantageous for abutment-implant stability and help decrease the rate of implant screw loosening (97).

Cantwell and Hobkirk noted that the most significant and rapid changes in preload occur within the initial 2 seconds. They also observed that the decrease in preload follows an exponential pattern over a longer duration. Specifically, the average preload loss within the first 15 hours was 24.9%; however, 29.5% of this loss occurred within the first 2 seconds, and 40.2% occurred within the first 10 seconds (35).

Tzenakis et al. reported that in an in vitro model system, approximately half of the preload is lost immediately after torque application, while the remainder is lost gradually over a 5-minute duration. Based on this observation, they recommended retightening the abutment screws 5 minutes after the initial torque application. They suggested that a longer interval between torque application and retightening could potentially lead to additional reductions in preload (120).

In order to reduce the settling effect, retightening of implant screw should be carried on 10 minutes prior to the initial torque application (90,96,97). This technique should be adopted as a routine clinical procedure.

### 2.13. Loosening Torque

Assessing the torque required for abutment loosening can be used as an indirect method to compare the preload force (55). According to Cibirka et al. an abutment's loosening torque can be used to indicate the stability of an implant-abutment connection (56).

If the loosening torque of an abutment is equal to the tightening torque or greater, it is a sign of a good long-term prognosis (57, 58). However, Sutter and others stated that a conventional implant design has a lower loosening torque than the initial tightening torque by 10%. Whereas, in the Morse taper implant systems the loosening torque is said to be greater than the initial tightening torque by 20% (59). The Morse taper systems were initially manufactured to increase the stability between an implant and abutment and simplify the prosthetic procedures. The latter properties of the Morse taper system occur due to the friction forces between the metal components or by cold fusion (60). This connection type is believed to increase the tolerance of loosening torque.

Kim et al. provided a study where 4 different internal tapered connections of solid and screwed abutments underwent mechanical fatigue tests. Their loosening torque was measured and compared before and after the test. What was found was that the average loosening torque prior to the test was 5% less than the initial tightening torque. However, after the mechanical fatigue test, the average loosening torque had increased by 10-15% compared to the initial torque. This could be explained by the cold fusion between the implant and the abutment (61).

Cerutti-Kopplin et al. studied 12 Morse taper implants with and without an anti- rotational component on their loosening torque measurements and grouped them separately. The study findings suggested that there was no significant statistical difference between the two groups. However, they found out that the loosening torque was less than the initial tightening torque without the application of a load (60).

Rodrigues Neto et al. studied a total of 20 implants with different interfaces where 5 were double hexagonal, 5 were octagonal and 10 were Morse taper. The initial tightening torque set by the manufacturers was 32 Ncm which they used for tightening all 20 implants. After 5 minutes they measured the loosening torque of each separate group. At the conclusion of the test, there was no significant statistical difference observed between the groups, nor between the initial and loosening torque values. It was deduced that the insignificance of the results was due to the small sample groups and lack of the mechanical load after the initial tightening torque (41).

### 2.14. Delivering Torque to the Implant-Abutment Complex

Torque is the rotational force generated with the application of a tangential force to a screw, typically measured in newton centimeters (Ncm) (94). With the purpose of delivering the target torque value to implant-abutment complex consistently, implant torque wrenches are used. Most common ones are spring-type (or beam-type) and friction-type torque wrenches. They are both activated by turning their spring clockwise. Spring-type torque wrenches provide different amount of torque values on the device to the user  Digital torque applicators emerged lately with eliminating the operator errors in mind, but some researchers concluded that still, they are inadequate in terms of delivering target torque to the implant-abutment (100).

### 2.15. Instron

Instron Universal Testing Machines is a well-known brand of materials testing equipment used in a variety of industries, including dentistry. Being a prominent global manufacturer in the material and structural testing markets, they offer a diverse range of testing equipment. Their product lineup includes universal testing machines, dynamic and fatigue testers, impact testing devices, rheology testing equipment, HDT and Vicat testers, automated testing systems, structural durability testing solutions, and crash simulation systems. In dental research, Instron machines are commonly used to test the strength and properties of dental materials such as composites, ceramics, and implants. While Instron is primarily designed for materials testing, it is possible to use it as a torque gauge in certain applications, such as in testing the torque resistance of dental implants or orthodontic wires.

To utilize an Instron Testing Machine as a torque gauge, fabrication of a custom fixture or an adapter is required. This custom fixture is affixed to the Instron Machine, serving to secure the device under test and quantify the applied torque. The fixture should be designed to apply the torque in a way that simulates the clinical situation as closely as possible, for example, by applying the torque to the implant or wire at a specific angle and direction.

Figure 2.8. displays the custom metal holder fixed to its place. Implant-abutment complex secured tight and stands horizontal in order to enable the system to receive the force appropriately. Instron's fixture is ready to apply pressure to the predetermined point on the implant torque wrench.


*Figure 2.8. Instron Model No 3345*

# 3. MATERIALS and METHODS

## 3.1. Materials

| **Materials** | **Manufacturer** |
|---|---|
| Seven XD implant internal hex ⌀4.2 | MIS Implants Technologies Ltd., Yehudah/Israel |
| Conical connection straight abutment ⌀4.3 | MIS Implants Technologies Ltd., Yehudah/Israel |
| Spring-style torque wrenches | MIS Implants Technologies Ltd., Yehudah/Israel |
| Manual hex screwdriver | MIS Implants Technologies Ltd., Yehudah/Israel |
| Standard abutment screws | MIS Implants Technologies Ltd., Yehudah/Israel |
| DTI-1 standard implant internal hex ⌀4.5 | DTI Implant System, TÜBİTAK Gebze/Kocaeli/Turkey |
| Anatomic straight abutment ⌀4.5 | DTI Implant System, TÜBİTAK Gebze/Kocaeli/Turkey |
| Spring-style torque wrenches | DTI Implant System, TÜBİTAK Gebze/Kocaeli/Turkey |
| Manual hex screwdriver | DTI Implant System, TÜBİTAK Gebze/Kocaeli/Turkey |
| Standard abutment screws | DTI Implant System, TÜBİTAK Gebze/Kocaeli/Turkey |
| T6 straight abutment ⌀5.0 | NucleOSS MKS Med. Kim. San.Tic. Ltd.Şti., Menderes/Izmir/Turkey |
| T6 standard bone level implant internal hex ⌀4.8 | NucleOSS MKS Med. Kim. San.Tic. Ltd.Şti., Menderes/Izmir/Turkey |
| Spring-style torque wrenches | NucleOSS MKS Med. Kim. San.Tic. Ltd.Şti., Menderes/Izmir/Turkey |
| Manual hex screwdriver | NucleOSS MKS Med. Kim. San.Tic. Ltd.Şti., Menderes/Izmir/Turkey |
| Standard abutment screws | NucleOSS MKS Med. Kim. San.Tic. Ltd.Şti., Menderes/Izmir/Turkey |
| Solid abutment ⌀4.5 | NTA Implant Tic. Ve San. Ltd. Şti., Muratpaşa/Antalya/Turkey |
| Regular bone level implant internal hex ⌀4.6 | NTA Implant Tic. Ve San. Ltd. Şti., Muratpaşa/Antalya/Turkey |
| Spring-style torque wrenches | NTA Implant Tic. Ve San. Ltd. Şti., Muratpaşa/Antalya/Turkey |
| Manual hex screwdriver | NTA Implant Tic. Ve San. Ltd. Şti., Muratpaşa/Antalya/Turkey |
| Standard abutment screws | NTA Implant Tic. Ve San. Ltd. Şti., Muratpaşa/Antalya/Turkey |
| Instron Model No. 3345 | Illinois Tool Works, Norwood/Massachusetts/USA |
| White Acrylic (self-cured) | Imicryl, Konya/Turkey |
| Custom metal holder | BALTECH, Hadımköy, Istanbul |
| DAC Professional Autoclave | Dentsply Sirona |

Table 3.1. Materials Used in the Study

### 3.2. Methods

This study involved the indirect assessment of various spring-style manual implant torque wrenches from different implant manufacturers. The evaluation focused on their torque-delivering capabilities of torque wrenches both before and after multiple cycles of steam sterilization.

This research was conducted at Prosthodontics Department of the Faculty of Dentistry at Yeditepe University, with experimental tests performed at the Yeditepe University Hard Tissue Laboratory in Istanbul, Turkey.

#### 3.2.1. Torque Wrenches and Screwdrivers Used in the Study

This study included the evaluation of implant torque wrenches from four distinct manufacturers to assess their precision in delivering target torque values and to examine variations in torque delivery following multiple steam sterilization cycles. The selected four dental implant manufacturers were NTA, NucleOSS, DTI and MIS Implants. Four torque wrenches, one manual screwdriver, and 80 abutment screws were collected from each brand. Selected torque wrenches from these brands were assigned a numerical identifier (1-4), while each manufacturer was denoted by a corresponding letter (A, B, C, D).

Samples of torque wrenches used in the study and their designs are shown in figure 3.1. While MIS and NucleOSS provided their custom torque wrench designs, DTI and NTA were using generic spring-style torque wrench designs.

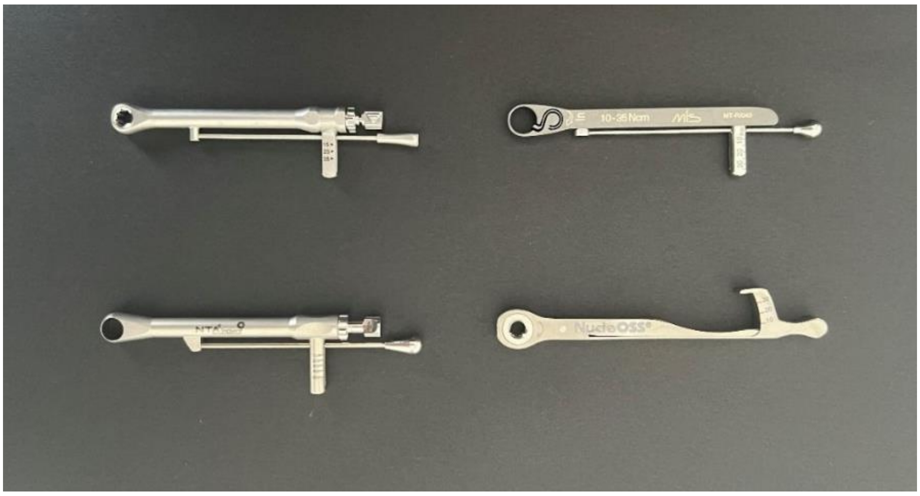


*Figure 3.1. Sample Torque Wrenches from Each Manufacturer (top left DTI (D), top right MIS (C), bottom left NTA(A) and, bottom right NucleOSS(B))*

This study exclusively opted for spring-type implant torque wrenches based on prior research findings indicating that friction-style torque wrenches are susceptible to greater deviations in target torque delivery results following exposure to multiple steam sterilization cycles. This susceptibility is attributed to the intricate inner components of friction-style torque wrenches compared to the simpler design of spring-style torque wrenches, as reported in previous studies (23).

The manual screwdrivers used in the study, from left to right DTI, NucleOSS, MIS, and NTA, with unique manual screwdriver-torque wrench connections are shown in figure 3.2. below.

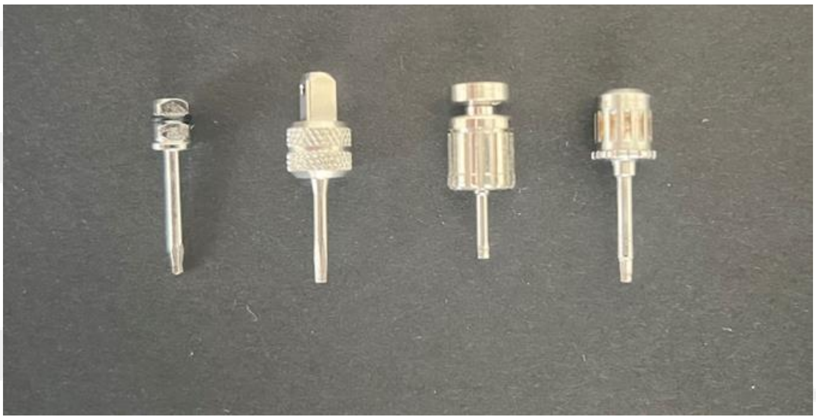

*Figure 3.2. Implant Screwdrivers used in the study.* From left to right DTI, NucleOSS, MIS, and NTA respectively.

## 3.3.Test Process

After assembling the test groups, devices, and materials, the implant bodies underwent preparation for the testing procedure. The first step involved securing the implant bodies in acrylic to enable fixation of the implant-abutment complex as a single unit in a precise location which aimed to standardize the process for each different group. This setup facilitated the system in receiving the force application from the Instron in the desired manner and magnitude. The operational parameters of the system were predetermined and overseen by the operator utilizing the computerized control system. The operator possessed the capacity to modulate the applied torque value and terminate the system upon attainment of the specified torque level, as visually represented on the graphical interface. Subsequent to the tightening of the implant screw, the operator transitioned to the loosening motion of the abutment screw, interpreting the graphical representation to determine the torque required for implant screw loosening during the torque application.

### 3.3.1. Preparing the Specimens

Implant bodies were embedded in self-cure acrylic (IMICRYL self-cure acrylic – white color) which was mixed and cast into metal rings, and then cured according to the guideline the manufacturer provided. To ensure the implants were embedded perpendicular to the horizon within the acrylic, a reference line was delineated parallel to the walls of the metal rings. Each implant was securely held in position with an apparatus aligned with the established reference line throughout the acrylic curing process. This measure aimed to counteract any potential discrepancies resulting from acrylic shrinkage, thereby achieving the intended structure parallel to the vertical line.

Acrylic was chosen as the surrogate for bone tissue. The specimens were cast into metal rings, ensuring a precise fit within the customized metal holder. The use of metal rings enabled the operator to secure the specimens firmly by employing a hex key for tightening. All implants were fixed in parallel orientation with each other and their corresponding metal rings’ inner walls in order to enable the Intron's application of force to the implant torque wrenches in a perpendicular manner when the specimens were mounted onto Instron with the custom metal holder.


*Figure 3.3. Imicryl self-cure acrylic*

*Figure 3.4. Embedded implant bodies that were used in the study.* From left to right, DTI, NucleOSS, NTA and MIS respectively.

Distinct markings were applied to each torque wrench at the point where it effectively received the specified force from the Instron. Consistently, each torque wrench was marked at an identical distance from the manual screwdriver, ensuring standardized force application. These durable markings facilitated the operator in replicating the same distance consistently, even after undergoing multiple cycles of steam sterilization and numerous repetitions. While delivering torque, Instron's force application was modified to be a flat and thin surface point to fit precisely in the marked area, which allowed the operator to repeat the same process for each individual repeated tightening motion.

### 3.3.2. Torque Application

In order to employ the Instron as a torque gauge, engineers at BALTECH company designed a custom metal holder using CAD software. This holder, laser-cut to specifications, was intended to secure the implants horizontally while exerting pressure with the Instron. With the implant abutment screwdriver and torque wrench in their place, the Instron executed the tightening motion of the torque wrenches by applying vertical pressure to the system.

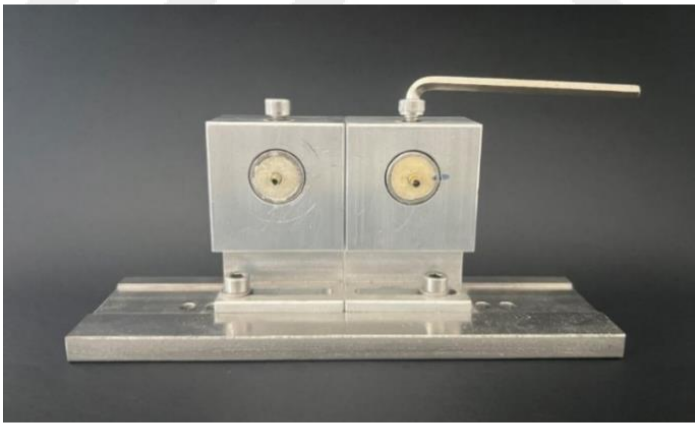

*Figure 3.5. Specimens Secured in Custom holder with the hex key.*

Following the secure fixation of the implant-abutment complex and the torque wrench onto the custom metal holder, the system was firmly stabilized. An allen hex key, which can be observed in Figure 3.5. Above, was employed to tighten the screw that secured the metal rings with embedded implant bodies to the custom metal holder. After the operator made sure that the system was tightened properly and the fixture of the system was completed, implant torque wrench was ready for testing.

Each torque wrench underwent an identical loading protocol, wherein the implant-abutment complex was tightened with each torque wrench through Instron compression. All trials were consistently carried out by the same operator. He halted the system when the desired torque value was reached in tightening and adjusted the wrench in reverse mode before loosening. Instron was set at the same speed both in tightening and in loosening.

By utilizing Instron for pressure application instead of only manual exertion, the aim of this method was to ensure uniform torque application across all trials, thereby minimizing potential operator errors that might arise during repeated tightening motions applied by hand.

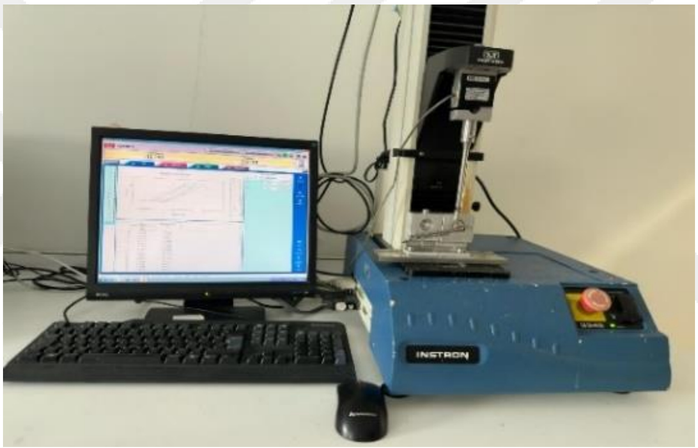


*Figure 3.6. Instron Testing Machine*

In the tightening step, the operator's primary responsibility was applying force until the target torque value was observed on the Instron's monitor. Even though the actual tests were performed using Instron, the operator prepared the torque wrenches before the initial tightening by adjusting their position manually to the system in order for the specimens to receive adequate force with minimal Instron movement.

To avoid torque loss resulting from the settling effect after the initial tightening, the operator re-tightened the abutment screw as earlier research suggested that a second tightening significantly increased the preload values. As time progressed a relative increase in preload value was observed after testing for 3-, 5-, and 10-minute intervals respectively (90,96,119). In order to optimize the ideal waiting time and preload value, this study opted for a 10-minute interval between torque applications. After the first tightening, the operator set a timer so he would know when to proceed to the second tightening. Figure 3.6. displays the loosening action by Instron, and tightening and loosening patterns of torque wrenches used in the study in form of a graphic.

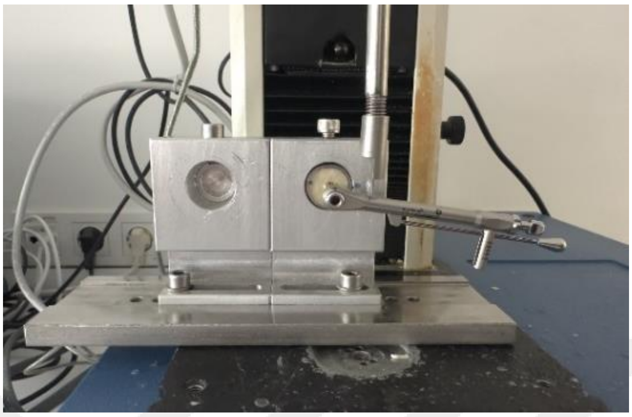

*Figure 3.7. Applying torque via Instron*

After the second tightening and the optimal preload value was reached, the implant torque wrenches were reversed to their loosening motion and then Instron was set to apply pressure to loosen the system. The torque delivery capacity of the implant torque wrenches was measured by recording the loosening torque which was the indirect method for torque evaluation. Torque wrenches from NucleOSS and NTA groups were tested at 25Ncm target torque value, while torque wrenches from MIS and DTI groups were tested at 30Ncm target torque value. The operator recorded the value where the loosening occurred. Each abutment screw was used only once. This aimed to prevent errors that might be caused by deformities in abutment screw.

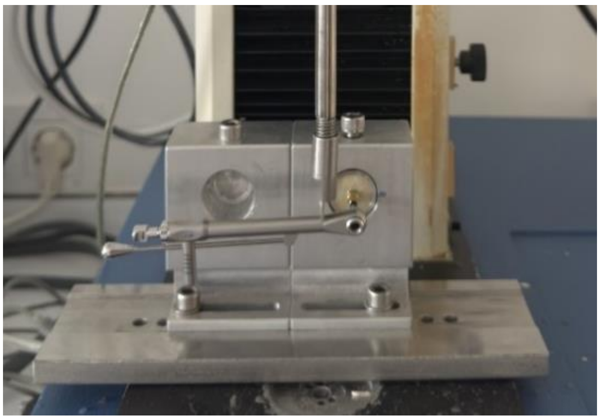

*Figure 3.8. Applying loosening torque via Instron*

Each trial comprised the following sequential steps:

1) Securing the implant-abutment complex in place.
2) Installing a new abutment screw.
3) Applying force perpendicularly to the system until the designated torque value was achieved using the Instron.
4) Allowing a 10-minute interval for the settling effect before reapplying pressure with the Instron until the target torque value was once again attained.
5) Reversing the torque wrench to initiate loosening motion and subsequently reattaching it to the implant-abutment complex.
6) While ensuring the torque wrench maintained a horizontal orientation, configuring the Instron to apply force from the same distance.
7) Allowing the Instron to apply force freely, observing the breakpoint of force application on the screen, and recording the corresponding value, denoting the loosening torque.
8) Disassembling and collecting the implant abutment screw.
9) Replicating the aforementioned steps for each subsequent trial.

After executing the steps explained above, 10 repetitions for each of the four torque wrenches from each of the four manufacturers, resulting in a total of 160 repetitions, torque wrenches were prepared for multiple steam sterilization cycles.

### 3.3.3. Steam Sterilization

Upon completion of the pre-steam sterilization tests for newly acquired torque wrenches, the specimens underwent preparation for a subsequent multiple steam sterilization protocol. Following the manufacturer's recommendations, all torque wrenches were prepared initially for steam sterilization by wrapping in autoclave packaging. Each torque wrench was prepared in individual packages. After packaging, torque wrenches constantly went under steam sterilization (Sirona DAC Professional Autoclave) protocol for 100 times. The autoclave's sterilization cycle was completed in 30 minutes which involved 5.5 minutes of sterilization under 2 bar sterilization pressure at 134 °C sterilization temperature. For each system, the manufacturer's guidelines were followed in between cycles. All 16 torque wrenches went under the same protocol for 100 times repeatedly.


*Figure 3.9. Sirona DAC Professional Autoclave*

### 3.3.4. After Steam Sterilization

Following exposure to multiple steam sterilization cycles, sterile packs were unsealed, and each torque wrench was collected and prepared for the second phase of subsequent testing.

Each specimen underwent a repetition of the identical testing procedure employed prior to exposure to multiple steam sterilization cycles. The same operator who conducted the tests before steam sterilization was responsible for the post-sterilization tests. Subsequently, each torque wrench from each implant manufacturer was retested with 10 consecutive measurements at the specified torque value. A new implant abutment screw was used between each test within each group.

Data obtained prior to sterilization and data obtained following sterilization were compared to see if there were any deviation from target torque values, applied torque values before the steam sterilization cycles, and after the steam sterilization cycles.

Figure 3.8. Below shows the torque wrenches grouped together in sterile packaging before and after multiple steam autoclave cycles. Color coded package indicators change from blue to black and from red to dark red after sterilization cycles.

*Figure 3.10. Torque wrenches from each brand before (left) and after (right) steam sterilization.*

Based on the power analysis conducted using the G*Power 3.1 program, the effect size for the deviation from the target torque value in the study group was determined to be 0.23 (alpha error=0.05). The analysis, utilizing an effect power of 0.80, indicated an optimal sample size totaling 160 measurements (10 measurements for each torque wrench from the four different manufacturers). Each torque wrench was used to tighten the abutment screws 10 times and then loosened 10 times prior to autoclave, total of 40 loosening evaluations for each manufacturer. After 100 cycles of autoclave meaning each torque wrench was retested and the raw data was gathered.

Absolute differences (target torque minus measured arithmetic difference as the dependent variable) were used as the outcome measures for accuracy. The statistical analysis for ANOVA was performed using JAMOVI (103). Data were analyzed using a repeated measures analysis of variance, with instrument as the repeated factor. Independent variables were the implant torque wrench status before and after multiple autoclave cycles. Furthermore, the percentage of deviation from the target torque value before and after autoclave was computed and compared against the target torque value.

Figures 3.11 and 3.12 illustrate examples from each trial conducted in the Instron machine. Breakpoints in the graphs are visible, with odd numbers representing the second tightening motion and even numbers indicating the loosening motion.

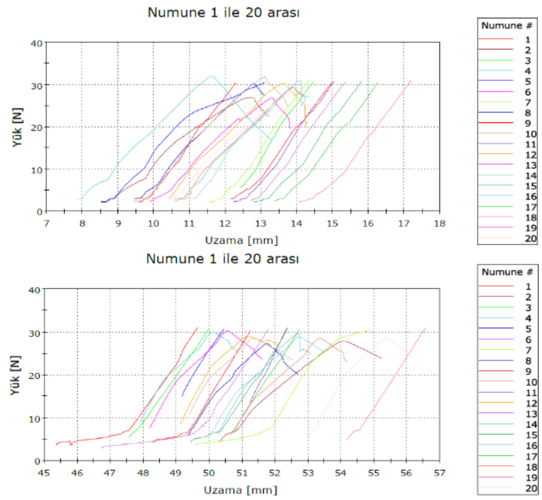


*Figure 3.11. Instron raw data and graphics from DTI and MIS*

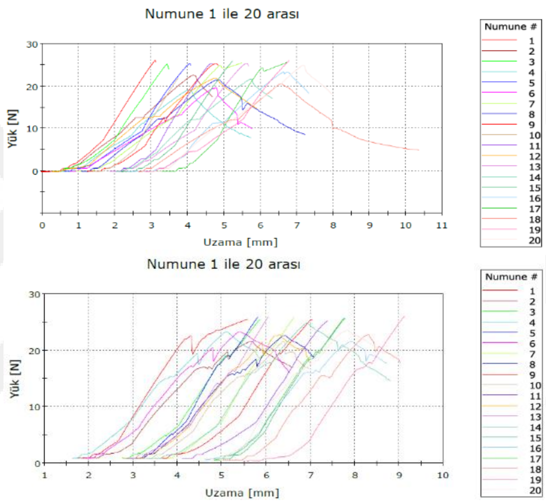


*Figure 3.11. Instron raw data and graphics from NTA and NucleOSS*

Torque measurements were gathered from 16 implant torque wrenches manufactured by four distinct dental implant companies to evaluate their precision in delivering specified torque values. During the data evaluation process, various statistical methods were used to determine the effect of multiple cycles of steam sterilization as the common factor which affects the same material at two different points in time. Descriptive statistics such as mean, standard deviation, median, and interquartile range were utilized to summarize and characterize the dataset. Additionally, the distribution of variables was assessed through the Shapiro-Wilk normality test.

For variables demonstrating a normal distribution, the paired t-test was employed to compare before-after autoclave and target torque value-loosening torque value, as well as in the comparison of paired groups. On the other hand, variables not conforming to normal distribution underwent comparison using the independent t-test and Kruskal-Wallis test for multiple group comparisons. Subgroup comparisons were conducted using Dunn's multiple comparison test, while the chi-square test was applied for the analysis of qualitative data. The significance level for interpreting results was set at $p<0.05$. In this study, statistical analyzes were performed with the NCSS (Number Cruncher Statistical System) 2007 Statistical Software (Utah, USA) package program.

# 4. RESULTS

## 4.1. Descriptive Statistics

Table 4.1. below shows univariate descriptive statistics of the variables used in the analysis. The variables include target torque values, and the loosening torque values before and after steam sterilization. In addition, changes between target and loosening torque values are calculated before and after the sterilization. The change values are calculated by dividing the loosening torque value by target torque value, then it is subtracted from 1. This value shows the percentage of the change.

The sample size is composed of 160 measurements. The target torque before autoclaving exhibits a mean value of 27.9, with a median and mode mirroring this central tendency at 27.9 and 25.1, respectively. The distribution displays a slight positive skewness of 0.0765, indicating a tendency for the data to skew towards higher torque values. The loosening torque before autoclaving is characterized by a mean of 25.8, with a median and mode of 25.4 and 19.1, respectively. The distribution, akin to the target torque, also shows a positive skewness of 0.0735. The change in torque before autoclave processes reveals a mean of 0.0765, a median of 0.0735, and a mode of 0.0450.

| | n | $\bar{x}$ | $\mp$ Sd | $S_E$ | min | max | median | skewness |
|---|---|---|---|---|---|---|---|---|
| Target Torque Value - Before Autoclave | 160 | 27.88 | 2.53 | 0.200 | 25.05 | 30.89 | 27.87 | 0.003 |
| Loosening Torque - Before Autoclave | 160 | 25.81 | 3.27 | 0.258 | 19.06 | 31.96 | 25.37 | -0.035 |
| Change - Before Autoclave | 160 | 0.08 | 0.05 | 0.004 | -0.05 | 0.24 | 0.07 | 0.396 |
| Target Torque Value - After Autoclave | 160 | 27.85 | 2.50 | 0.198 | 25.05 | 30.58 | 27.89 | 0.001 |
| Loosening Torque - After Autoclave | 160 | 25.34 | 3.55 | 0.280 | 18.40 | 31.86 | 25.67 | -0.127 |
| Change - After Autoclave | 160 | 0.09 | 0.06 | 0.005 | -0.05 | 0.27 | 0.08 | 0.553 |

*Table 4.1. Descriptive Statistics*

### 4.2. ANOVA Test

Paired ANOVA tests are conducted due to the presence of the same measurements at two distinct time points. Initially, an examination of between-subject effects is undertaken across four different brands. The obtained p-value, which is less than 0.001, shows a significant effect. The partial effect size attributed to the brand variable is notably high at 0.414, indicating significant distinctions among the four brands. This disparity is visually represented in Table 4.2. wherein the means and corresponding confidence intervals are displayed. Notably, DTI and MIS exhibit similar patterns, distinguishing themselves from NTA and NucleOSS, the latter two also displaying a comparable pattern

Between Subjects Effects

| | Sum of Squares | df | Mean Square | F | p | $\eta^2_p$ |
|---|---|---|---|---|---|---|
| Brand | 0.289 | 3 | 0.096 | 36.7 | < .001 | 0.414 |
| Residual | 0.410 | 156 | 0.003 | | | |

*Note.* Type 3 Sums of Squares

*Table 4.2. ANOVA Between Subjects*

Within Subjects Effects

| | Sum of Squares | df | Mean Square | F | p | $\eta^2_p$ |
|---|---|---|---|---|---|---|
| time | 0.023 | 1 | 0.023 | 9.30 | 0.003 | 0.056 |
| time ✻ Brand | 0.016 | 3 | 0.005 | 2.20 | 0.091 | 0.041 |
| Residual | 0.384 | 156 | 0.002 | | | |

*Note.* Type 3 Sums of Squares

*Table 4.3. ANOVA Within Subjects*

In the second step we investigated the effect of time: Before and after steam sterilization cycles. We see after sterilization results showed that change is much higher than before. This is shown in figure 4.2. When we look at the figure of time, we ignore figure 4.1. and vice versa.

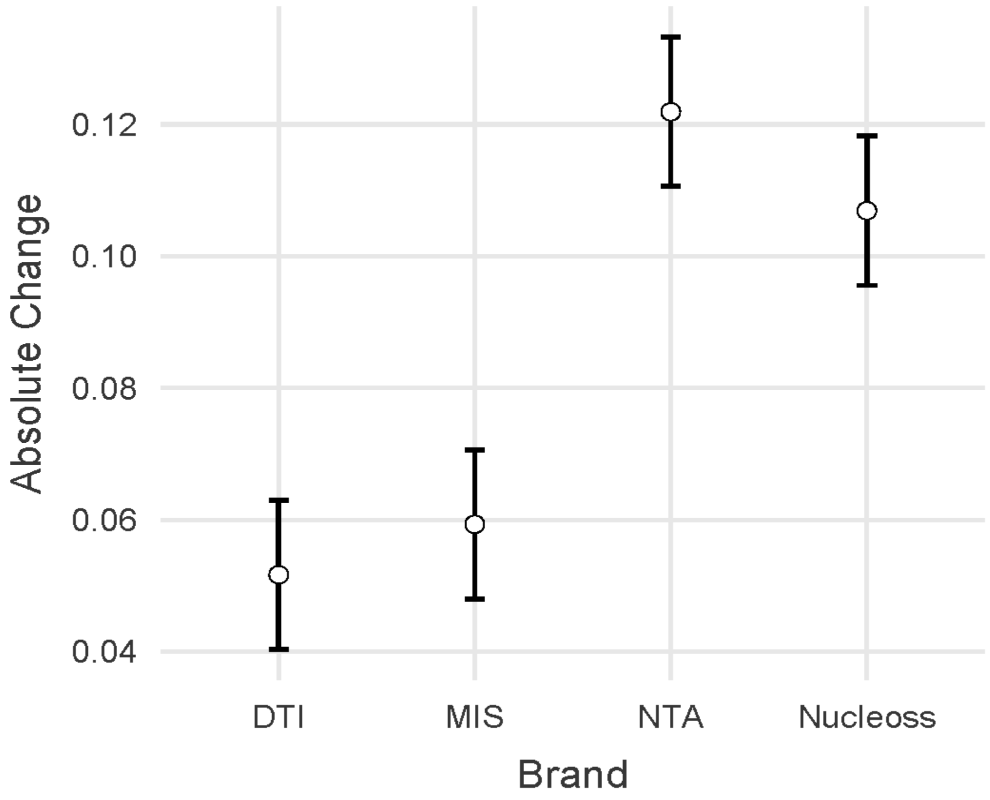


*Figure 4.1. Absolute Change of Brands*

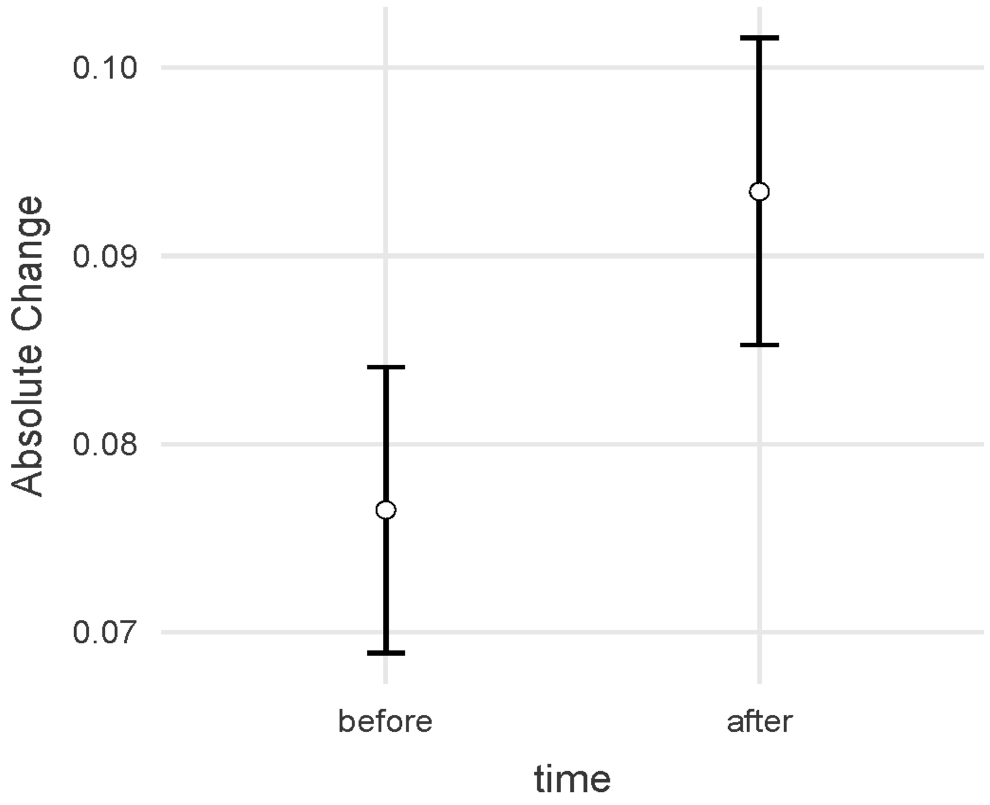


*Figure 4.2. Absolute Change Before and After Autoclave*

In the final stage, we examine the interaction effect between time and brands. When considered in conjunction with time, there is no statistically substantial disparity between DTI and MIS brands. This information is detailed in Figure 4.3.

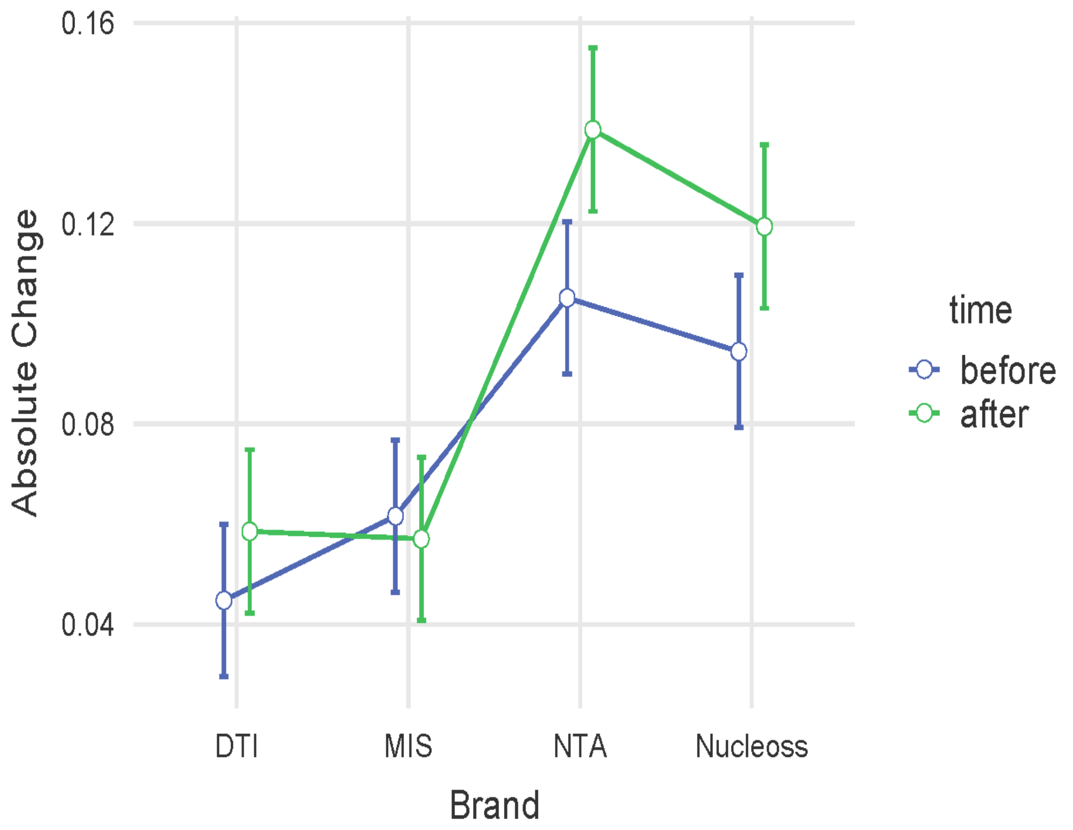


*Figure 4.3. Time and Brand Interaction Effect*

This finding can also be found in table 4.4. below with Bonferroni Post Hoc Analysis values for time and brand interactions.

Post Hoc Comparisons - time ✻ Brand

| Comparison | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| time | Brand | time | Brand | Mean Difference | SE | df | t | p | $p_{bonferroni}$ |
| before | DTI | - before | MIS | -0.017 | 0.011 | 156 | -1.547 | 0.124 | 1.000 |
| | | - before | NTA | -0.060 | 0.011 | 156 | -5.550 | < .001 | < .001 |
| | | - before | Nucleoss | -0.050 | 0.011 | 156 | -4.567 | < .001 | < .001 |
| | | - after | DTI | -0.014 | 0.011 | 156 | -1.241 | 0.216 | 1.000 |
| | | - after | MIS | -0.012 | 0.011 | 156 | -1.088 | 0.278 | 1.000 |
| | | - after | NTA | -0.094 | 0.011 | 156 | -8.325 | < .001 | < .001 |
| | | - after | Nucleoss | -0.075 | 0.011 | 156 | -6.612 | < .001 | < .001 |
| | MIS | - before | NTA | -0.044 | 0.011 | 156 | -4.003 | < .001 | 0.003 |
| | | - before | Nucleoss | -0.033 | 0.011 | 156 | -3.020 | 0.003 | 0.083 |
| | | - after | DTI | 0.003 | 0.011 | 156 | 0.270 | 0.787 | 1.000 |
| | | - after | MIS | 0.004 | 0.011 | 156 | 0.410 | 0.682 | 1.000 |
| | | - after | NTA | -0.077 | 0.011 | 156 | -6.834 | < .001 | < .001 |
| | | - after | Nucleoss | -0.058 | 0.011 | 156 | -5.121 | < .001 | < .001 |
| | NTA | - before | Nucleoss | 0.011 | 0.011 | 156 | 0.984 | 0.327 | 1.000 |
| | | - after | DTI | 0.047 | 0.011 | 156 | 4.130 | < .001 | 0.002 |
| | | - after | MIS | 0.048 | 0.011 | 156 | 4.263 | < .001 | < .001 |
| | | - after | NTA | -0.034 | 0.011 | 156 | -3.023 | 0.003 | 0.082 |
| | | - after | Nucleoss | -0.014 | 0.011 | 156 | -1.261 | 0.209 | 1.000 |
| | Nucleoss | - after | DTI | 0.036 | 0.011 | 156 | 3.182 | 0.002 | 0.049 |
| | | - after | MIS | 0.037 | 0.011 | 156 | 3.315 | 0.001 | 0.032 |
| | | - after | NTA | -0.044 | 0.011 | 156 | -3.922 | < .001 | 0.004 |
| | | - after | Nucleoss | -0.025 | 0.011 | 156 | -2.246 | 0.026 | 0.731 |
| after | DTI | - after | MIS | 0.002 | 0.012 | 156 | 0.129 | 0.898 | 1.000 |
| | | - after | NTA | -0.080 | 0.012 | 156 | -6.867 | < .001 | < .001 |
| | | - after | Nucleoss | -0.061 | 0.012 | 156 | -5.211 | < .001 | < .001 |
| | MIS | - after | NTA | -0.087 | 0.012 | 156 | -6.995 | < .001 | < .001 |
| | | - after | Nucleoss | -0.062 | 0.012 | 156 | -5.340 | < .001 | < .001 |
| | NTA | - after | Nucleoss | 0.019 | 0.012 | 156 | 1.656 | 0.100 | 1.000 |

*Table 4.4 Post Hoc Analysis*

### 4.3. Paired Sample t-test and Independent-samples t-test

Paired samples t-test was employed to compare the means of two measurements derived from the same individual, object, or related units. In this study, tests were conducted on identical objects at two distinct time points, effect of time was multiple autoclave cycles. The objective of this test was to decide whether there existed statistical evidence indicating that the mean difference between paired observations significantly deviated from zero.

The independent sample t-test served to compare means between two distinct samples from unrelated groups, with individual scores contributed by separate individuals within each group. Its purpose was to determine if there were statistically significant differences between the compared samples.

| | Applied Torque | DTI | MIS | p* |
|---|---|---|---|---|
| | **Before Autoclave** | 30,43±0,15 | 30,37±0,16 | 0,093 |
| | **After Autoclave** | 30,37±0,16 | 30,32±0,13 | 0,154 |
| **Target Torque** | **p†** | 0,105 | 0,214 | |
| | **Before Autoclave** | 29,06±1,28 | 28,5±1,28 | 0,054 |
| | **After Autoclave** | 28,59±1,11 | 28,59±1,24 | 0,999 |
| **Loosening Torque** | **p†** | 0,067 | 0,635 | |

*** Independent variable t-test †Paired sample t-test**

*Table 4.2. T-Tests of DTI and MIS groups*

There was no notable statistical variance found between the target torque before-autoclave averages of the DTI and MIS groups (p = 0.093).

There was no notable statistical variance found between the after-autoclave target torque value averages of the DTI and MIS groups (p = 0.154).

There was no statistically meaningful change observed between the DTI group's before and after-autoclave target torque value averages (p=0.105).

There was no statistically meaningful change detected between the before and after-autoclave target torque value averages of the MIS group (p=0.214).

There was no notable statistical variance found between the before-autoclave loosening torque value averages of the DTI and MIS groups (p = 0.054).

There was no notable statistical variance found between the after-Autoclave loosening torque value averages of the DTI and MIS groups (p = 0.999).

The analysis did not reveal any statistically significant distinction in before and after-autoclave loosening torque value averages of the DTI group (p = 0.067).

The analysis did not reveal any statistically notable distinction in before and after-autoclave loosening torque value averages of the MIS group (p = 0.635).

Figure 4.4. below shows the applied target torque values before and after multiple cycles of steam sterilization.

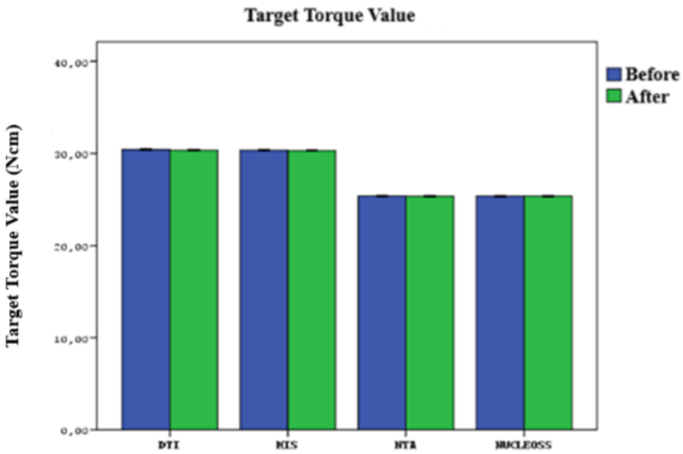


*Figure 4.4. Applied Target Torque Values Before and After Autoclave*

| | Applied Torque | NTA | NUCLEOSS | p |
|---|---|---|---|---|
| Target Torque | **Before Autoclave** | 25,37±0,12 | 25,36±0,12 | 0,600 |
| | **After Autoclave** | 25,36±0,15 | 25,37±0,1 | 0,701 |
| | **p†** | 0,595 | 0,053 | |
| Loosening Torque | **Before Autoclave** | 22,71±1,37 | 22,96±1,41 | 0,410 |
| | **After Autoclave** | 21,84±1,77 | 22,34±1,37 | 0,160 |
| | **p†** | 0,739 | 0,063 | |

*** Independent variable t-test †Paired sample t-test**

*Table 4.6. T- Tests of NTA and NucleOSS groups*

There was no notable statistical variance found between the before-autoclave applied target torque value averages of the NTA and NucleOSS groups (p = 0.600).

There was no notable statistical variance found between the after-autoclave applied target torque value averages of the NTA and NucleOSS groups (p = 0.701).

There was no statistically significant change found between the average target applied torque values of the NTA group before and after autoclaving (p=0.595).

There was no statistically considerable change found between the average target applied torque values of the NucleOSS group before and after autoclaving (p=0.053).

There was no notable statistical variance found between the before-autoclave measurement target applied torque value averages of the NTA and NucleOSS groups (p = 0.410).

There was no notable statistical variance found between the after-autoclave measurement target applied torque value averages of the NTA and NucleOSS groups (p = 0.160).

No statistically significant change was observed between the before and after-autoclave target torque value averages measured in the NTA group (p = 0.739).

No statistically significant change was observed between the before and after-autoclave target torque value averages measured in the NucleOSS group. (p=0.063).

#### 4.3.1. Paired Sample T-Test

| | **Before Autoclave** | | | **After Autoclave** | | |
|---|---|---|---|---|---|---|
| | **Target Torque** | **Loosening Torque** | **p†** | **Target Torque** | **Loosening Torque** | **p†** |
| **DTI** | 30,43±0,15 | 29,06±1,28 | **0,0001** | 30,37±0,16 | 28,59±1,11 | **0,0001** |
| **MIS** | 30,37±0,16 | 28,50±1,28 | **0,0001** | 30,32±0,13 | 28,59±1,24 | **0,0001** |
| **NTA** | 25,37±0,12 | 22,71±1,37 | **0,0001** | 25,36±0,15 | 21,84±1,77 | **0,0001** |
| **NucleOSS** | 25,36±0,12 | 22,96±1,41 | **0,0001** | 25,37±0,1 | 22,34±1,37 | **0,0001** |

***Paired sample t-test**

*Table 4.3. Paired Sample T-test Before-Autoclave Loosening Averages*

Figure 4.5. below shows the loosening torque values. Blue columns represent the loosening torque value averages before multiple cycles of autoclave for each brand and green columns represent the loosening torque value averages after multiple cycles of autoclave for each brand.

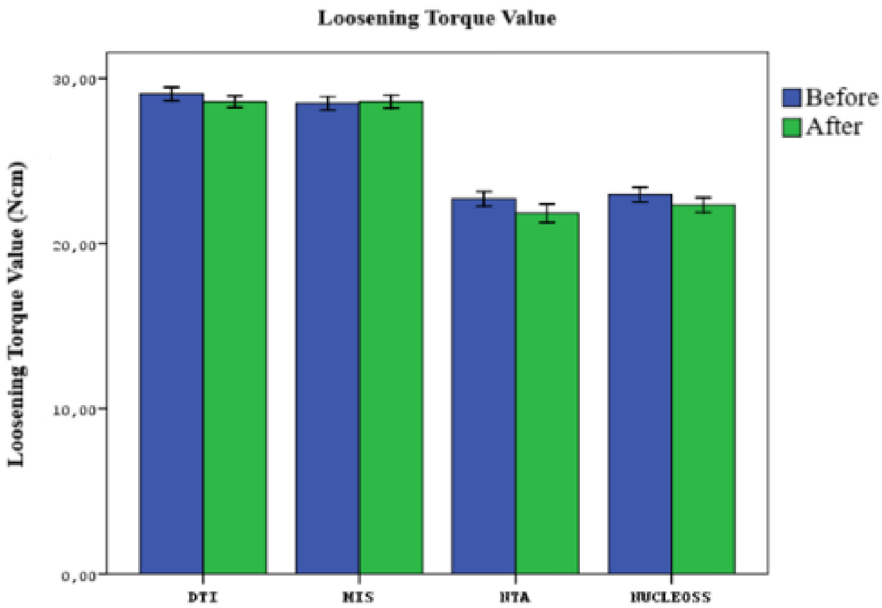


*Figure 4.5. Loosening Torque Values Before and After Steam Sterilization*

Before-autoclave measurements of loosening torque averages of the DTI group reported statistically significant differences, being lower than the target torque value averages ($p = 0.0001$).

Before-autoclave measurements of loosening torque averages of the MIS group showed a statistically significant decrease compared to the target torque value averages ($p=0.0001$).

Before-autoclave measurements of loosening torque averages of the NTA group exhibited statistically significant reduction compared to the target torque value averages ($p = 0.0001$).

Before-autoclave measurements of loosening torque averages of the NucleOSS group demonstrated a statistically significant decline relative to the target torque value averages ($p = 0.0001$).

After-autoclave measurements of loosening torque averages of the DTI group reported statistically significant differences, being lower than the applied target torque value averages (p=0.0001).

After-autoclave measurements of loosening torque averages of the MIS group showed a statistically significant decrease compared to the applied target torque value averages (p=0.0001).

After-autoclave measurements of loosening torque averages of the NTA group exhibited statistically significant reduction compared to the applied target torque averages (p=0.0001).

After-autoclave measurements of loosening torque averages of the NucleOSS group demonstrated a statistically significant decline relative to the applied target torque value averages (p=0.0001).

Figure 4.6. below shows us applied target torque values and loosening torque values for each manufacturer before and after steam sterilization cycles.

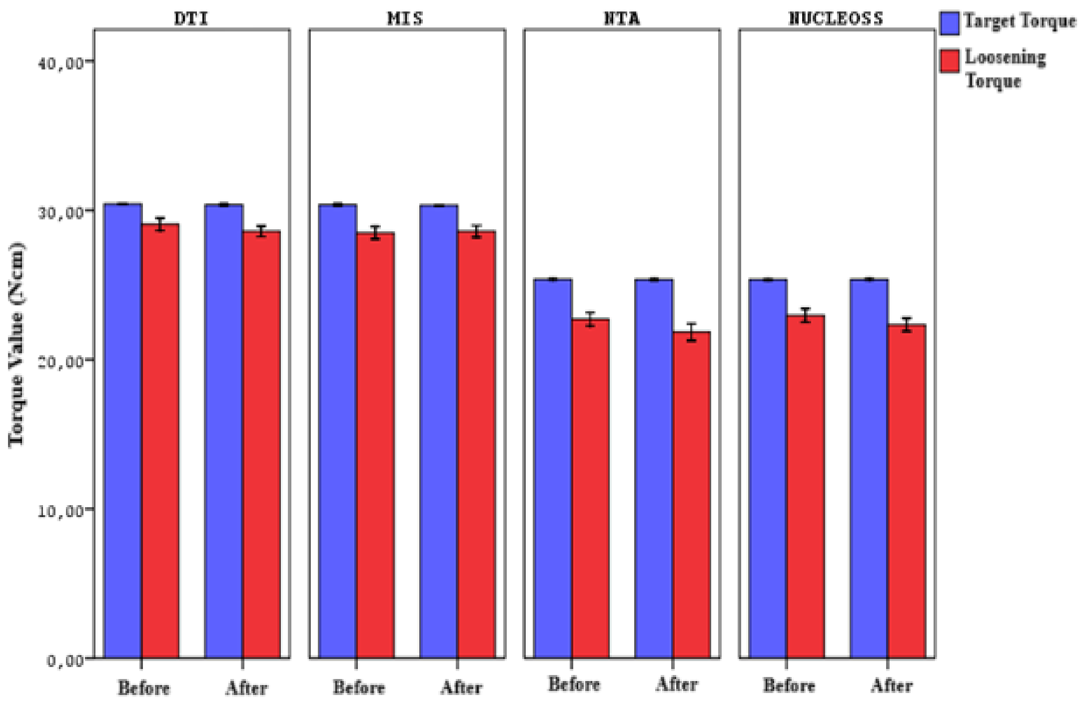


*Figure 4.6. Applied Torque Values and Loosening Torque Values of Brands*

### 4.4.Kruskal-Wallis Test and Dunn's Test

Kruskal-Wallis test was utilized to see whether the four independent samples with equal size originated from the same distribution. Following the rejection of Kruskal-Wallis test, post hoc procedure Dunn's test was performed for multiple comparisons.

| | **Target Torque Value – Loosening Torque Value** | | | |
|---|---|---|---|---|
| | **Before-Autoclave Difference** | | **After-Autoclave Difference** | |
| | **Mean±Sd** | **Median (IQR)** | **Mean±Sd** | **Median (IQR)** |
| **DTI** | 1,36±1,26 | 1,4 (0,48-2,37) | 1,78±1,11 | 1,9 (1,19-2,66) |
| **MIS** | 1,87±1,27 | 1,98 (0,92-2,77) | 1,73±1,23 | 1,88 (0,99-2,61) |
| **NTA** | 2,67±1,34 | 2,46 (2-3,38) | 3,52±1,79 | 3,6 (2,16-4,77) |
| **NUCLEOSS** | 2,40±1,44 | 2,04 (1,27-3,84) | 3,03±1,39 | 2,98 (2,01-4,08) |
| **p** | **0,0001** | | **0,0001** | |

‡ **Kruskall Wallis Test**

*Table 4.4. Kruskall Wallis Test Before-After Autoclave Averages*

| | **Target Torque Value-Loosening Torque Value** | |
|---|---|---|
| **Dunn's Test** | **Difference before autorclave** | **Difference after autoclave** |
| **DTI / MIS** | 0,131 | 0,795 |
| **DTI / NTA** | **0,0001** | **0,0001** |
| **DTI / NUCLEOSS** | **0,004** | **0,0001** |
| **MIS / NTA** | **0,007** | **0,0001** |
| **MIS / NUCLEOSS** | 0,157 | **0,0001** |
| **NTA / NUCLEOSS** | 0,326 | 0,233 |

*Table 4.5. Post Hoc Dunn's Test Before-After Difference Comparison*

There was a notable statistical difference found in the before-autoclave target torque and loosening torque value difference averages among the DTI, MIS, NTA, and NucleOSS groups (p = 0.0001). Specifically, the DTI group exhibited significantly lower mean differences in before-autoclave target torque and loosening torque values compared to the NTA and NucleOSS groups (p = 0.0001, p = 0.004). Similarly, the MIS group's mean differences in before-autoclave target torque and loosening torque values were significantly lower than those of the NTA group (p = 0.007). There were no statistically notable distinctions observed between the remaining groups (p > 0.05).

| | **Target Torque Value – Loosening Torque Value** | | | |
|---|---|---|---|---|
| | **Absolute Difference Before Autoclave** | | **Absolute Difference After Autoclave** | |
| | **Mean±Sd** | **Median (IQR)** | **Mean±Sd** | **Median (IQR)** |
| **DTI** | 1,6±0,94 | 1,48 (0,9-2,37) | 1,87±0,93 | 1,9 (1,19-2,66) |
| **MIS** | 1,94±1,16 | 1,98 (1,05-2,77) | 1,87±0,99 | 1,88 (1,06-2,61) |
| **NTA** | 2,67±1,33 | 2,46 (2-3,38) | 3,52±1,79 | 3,6 (2,16-4,77) |
| **NUCLEOSS** | 2,40±1,44 | 2,04 (1,27-3,84) | 3,03±1,39 | 2,98 (2,01-4,08) |
| **p** | **0,0001** | | **0,0001** | |

**‡Kruskal Wallis Test**

*Table 4.6 Absolute Difference Before-After Autoclave*

| | **Target Torque Value – Loosening Torque Value** | |
|---|---|---|
| **Dunn's Test** | **Absolute Difference Before Autoclave** | **Absolute Difference After Autoclave** |
| **DTI / MIS** | 0,214 | 0,885 |
| **DTI / NTA** | **0,0001** | **0,0001** |
| **DTI / NUCLEOSS** | **0,012** | **0,0001** |
| **MIS / NTA** | **0,007** | **0,0001** |
| **MIS / NUCLEOSS** | 0,184 | **0,0001** |
| **NTA / NUCLEOSS** | 0,326 | 0,233 |

*Table 4.7. Post Hoc Dunn's Test Absolute Difference Before-After Autoclave*

The preceding discussion focused on the difference averages before autoclave cycles. A statistically meaningful distinction was evident in the after-autoclave target torque and loosening torque value difference averages among the DTI, MIS, NTA, and NucleOSS groups (p=0.0001). Specifically, the after-autoclave target torque and loosening torque value difference averages of the DTI group were significantly lower than those of the NTA and NucleOSS groups (p=0.0001). Similarly, the after-autoclave target torque and loosening torque value difference averages of the MIS group were also significantly lower than those of the NTA and NucleOSS groups (p=0.0001). No statistically significant difference was observed between the other groups (p>0.05).

A statistically significant disparity was observed in the before-autoclave absolute difference averages between the target torque and loosening torque values of the DTI, MIS, NTA, and NucleOSS groups (p = 0.0001). Specifically, the before-autoclave target torque and loosening torque value absolute difference averages of the DTI group were significantly lower than those of the NTA and NucleOSS groups (p = 0.0001, p = 0012). Similarly, the before-autoclave target torque and loosening torque value absolute difference means of the MIS group were significantly lower than those of the NTA group (p = 0.007). No statistically significant difference was observed between the other groups (p > 0.05).

| | **Difference Between Before-After Autoclave (%)** | |
|---|---|---|
| | **Mean±Sd** | **Median (IQR)** |
| **DTI** | 1,45±5,51 | 2,05 (-1,39-4,73) |
| **MIS** | -0,45±4,58 | -0,33 (-2,05-1,65) |
| **NTA** | 3,41±10,48 | 2,26 (-3,02-10,19) |
| **NUCLEOSS** | 2,35±8,73 | 3,72 (-3,89-8,25) |
| **p** | **0,048** | |

**‡Kruskal Wallis Test**

*Table 4.8. Difference ratio before-after autoclave*

The discussion regarding absolute differences before autoclave was presented earlier, and the subsequent discussion pertains to results post-autoclave: A statistically significant absolute difference was identified in the after-autoclave target torque and loosening torque value absolute difference averages among the DTI, MIS, NTA, and NucleOSS groups (p=0.0001). Specifically, the after-autoclave target torque and loosening torque value absolute difference averages of the DTI group were significantly lower than those of the NTA and NucleOSS groups (p=0.0001). Similarly, the after-autoclave target torque and loosening torque value absolute difference averages of the MIS group were significantly lower than those of the NTA and NucleOSS groups (p=0.0001). No statistically significant difference was observed between the other groups (p>0.05).

There was a statistically significant distinction noted between the before and after-autoclave loosening torque value averages of the DTI, MIS, NTA and NucleOSS groups (p = 0.0001). The before and after-autoclave loosening torque value difference averages of the MIS group were found to be statistically significantly lower than the DTI, NTA and NucleOSS groups (p = 0.021, p = 0.048, p = 0.015), and there were no significant absolute differences exhibited in variations compared to the other groups. (p >0.05).

| **Dunn's Test** | **Difference Between Before-After Autoclave (%)** |
|---|---|
| **DTI / MIS** | **0,021** |
| **DTI / NTA** | 0,465 |
| **DTI / NucleOSS** | 0,285 |
| **MIS / NTA** | **0,048** |
| **MIS / NucleOSS** | **0,015** |
| **NTA / NucleOSS** | 0,832 |

*Table 4.9. Post Hoc Dunn's Test Difference Ratio*

### 4.5. Chi-Square Test

In the qualitative evaluation of subgroups, a chi-squared test was utilized to assess the concordance between observed and expected values. The subsequent test results delineate the quantity of samples surpassing or falling below the targeted 10% range of their intended target torque delivery capabilities, along with their respective ratios within their distinct groups. This analysis highlights the variations before and after subjecting the specimens to multiple cycles of autoclave.

A statistically meaningful discrepancy was noted between the before and after-autoclave loosening torque value difference % distributions of DTI, MIS, NTA and NucleOSS groups (p = 0.0001). Before and after-autoclave loosening torque value difference <10% in the DTI and MIS groups was found to be lower than the NTA and NucleOSS groups.

Figure 4.7. below displays the results of the Chi-Square test comparing loosening torque values before and after multiple cycles of steam sterilization, demonstrating the percentage change in the value.

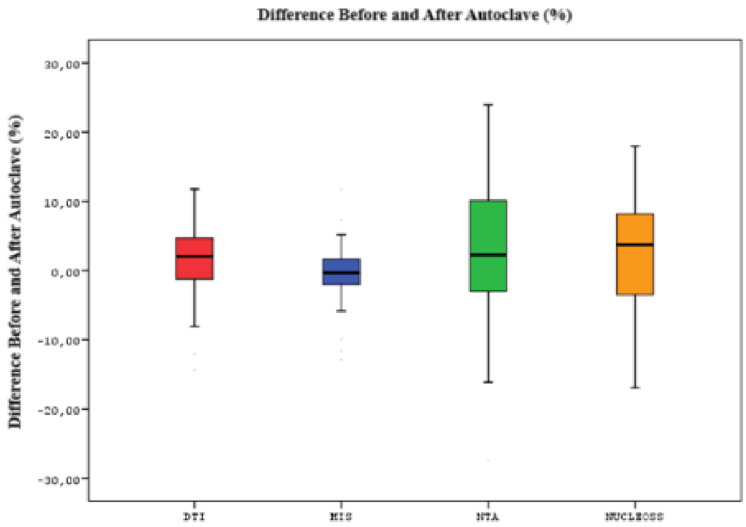


*Figure 4.7. Chi-Square Test for Loosening Torque Deviations*

In the following table 4.14. DTI and MIS groups both had the same number of variations with more than a 10% difference from their torque values. NTA had 12 trials (30%) with more than a 10% range difference from its target torque. The group that demonstrated the most variation was NucleOSS, with 14 of their trials (35%) exceeding the 10% range of their target torque.

| | | DTI | | MIS | | NTA | | NUCLEOSS | | P |
|---|---|---|---|---|---|---|---|---|---|---|
| **Difference between before-after autoclave** | **<%10** | 37 | 92,50% | 37 | 92,50% | 28 | 70,00% | 26 | 65,00% | |
| | **>%10** | 3 | 7,50% | 3 | 7,50% | 12 | 30,00% | 14 | 35,00% | **0,0001** |

***Table 4. 10. *Chi-Square test for 10% threshold***

Figure 4.8. below indicates the trials that manage to stay within 10% range of target torque value before and after steam sterilization. While all trials managed to stay within the 10% range, a statistically significant distinction was noted in the percentage distributions of loosening torque differences before and after steam sterilization among the DTI, MIS, NTA, and NucleOSS groups ($p = 0.0001$). Specifically, the proportion of before and after-steam sterilization loosening torque differences below 10% in the DTI and MIS groups was observed to be lower than in the NTA and NucleOSS groups.

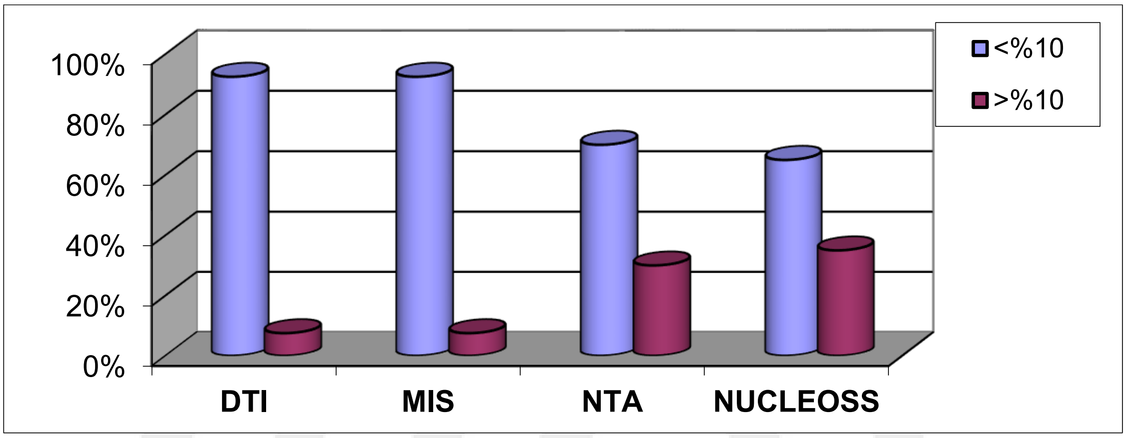


*Figure 4.8. Scaling of trials that managed to stay within 10%.*

# 5. DISCUSSION

The aim of this study was to investigate the effect of multiple steam sterilization cycles on the efficacy of torque wrenches used in dental implant procedures. Our findings highlight the significant impact of brand selection on torque delivery values, particularly following repetitive exposures to heat.

The repeated ANOVA tests were conducted to analyze measurements taken at two different time points. Initially, between-subject effects were examined across four distinct brands. A significant effect was found indicating significant differences among the four implant brands utilized in this study.

The results of the repeated ANOVA tests suggest that the choice of brand significantly influences the measured outcomes across the two time points. The high partial effect size indicates that brand selection accounts for a substantial proportion of the variance in the data. Additionally, the visual representation in Figure 4.3. clearly illustrates distinct patterns among the four brands, with DTI and MIS showing similar trends and NTA and NucleOSS exhibiting comparable patterns.

Standlee et al. conducted an evaluation of three mechanical devices to assess the accuracy of torque application. Their findings indicated that both spring-style torque wrenches and friction-style wrenches were within 10% of the target torque values (5). Staying within 10% range was accepted as clinical success by other authors (6,7,23). On the other hand, Santos et al. showed a degree of inaccuracy in various tested spring-style torque wrenches (Biomet 3i, Nobel Biocare, Straumann, and Conexao). For target torque values of 20 Ncm, 62.5% of measured values were accurate (within 10% of the target torque value). However, for a target torque of 32 Ncm, only one-third of values from each manufacturer were deemed accurate (137).

The initial null hypothesis was there would not be a statistically significant difference between tightening and loosening torque values before multiple autoclave cycles. Before autoclaving, there were variations in both tightening and loosening torque values, but each torque wrench consistently delivered torque within an average of 10% of the target torque value, without any greater variations.

In the qualitative evaluation of subgroups, a chi-squared test was utilized to assess the concordance between observed and expected values. While all brands in this study managed to stay within 10% of their target torque range in average, which is acceptable for the clinical outcome, some trials still exhibited variations exceeding 10% from the target torque values. The MIS and DTI groups exhibited a lower level of deviation from the 10% range of their target torque value, with 7.5% on average. NTA showed a higher deviation of 30%, while NucleOSS had the most frequent difference of 35% in all trials.

The second null hypothesis was there would be no statistically significant change in torque delivery capacities of implant torque wrenches after multiple cycles of steam sterilization. Each torque wrench was affected by steam sterilization. The NTA and NucleOSS groups exhibited the most deviations, although on average all groups remained within the range of less than 10% difference from their target torque values.

The after-autoclave target torque and loosening torque value absolute difference averages of the DTI group were significantly lower than those of the NTA and NucleOSS groups (p=0.0001). Similarly, the after-autoclave target torque and loosening torque value absolute difference averages of the MIS group were significantly lower than those of the NTA and NucleOSS groups (p=0.0001). There was no statistically significant difference observed between the other groups ($p > 0.05$). This suggests that both the DTI and MIS groups maintained better control over their target torque values after autoclaving compared to the NTA and NucleOSS groups. The brand that demonstrated the greatest change in torque delivery averages before and after steam sterilization was NTA, followed by NucleOSS. MIS and DTI exhibited similar levels of deviation, and lower than those observed in NTA and NucleOSS.

This interpretation suggests that there are meaningful differences in the performance or response of the tested brands over 100 cycles of steam sterilization, highlighting the importance of brand selection in influencing outcomes. Specimens that were tested at 30Ncm torque values exhibited better rates both before and after steam sterilization than the specimens that were tested at 25Ncm torque values. Even though the applications of excessive torque can also result in unintentional screw loosening, opting for manufacturers that recommend higher torque values for their products may lead to better outcomes.

The third null hypothesis was there would not be a difference between brands in their torque delivery capacities. Figure 4.3. demonstrates the absolute differences of brands both before and after autoclaving, it can be observed that each brand performed differently. The brands that demonstrated the closest performance to each other were DTI and MIS.

The choice of brand can indeed influence several outcomes, as factors such as material design and selection can vary significantly between different brands, leading to differences in performance and accuracy of torque wrenches. Some brands design their torque wrenches and their connections to manual screwdrivers with additional screws to secure the ratchet and case together. Conversely, other torque wrenches are manufactured as one solid unit with intricate parts to accommodate a manual screwdriver. These design differences may result in varied reactions under repeated use and multiple cycles of steam sterilization.

Screw material plays a crucial role in performance of the screw, particularly concerning preload values. Screws with surface treatment, or the screw material can have a significant impact on preload values especially after repeated use. The primary limitations of titanium alloys lie in their inadequate friction and wear resistance, posing difficulties in attaining substantial preload values with titanium screws. (107). To address this, some manufacturers offer carbon-coated screws with a diamond-like carbon surface (110). Additionally, gold or gold-coated screws, when subjected to equal torque, have been reported to achieve higher preload values than titanium screws, with some cases showing even higher preloads than coated titanium screws (121). Prosthetic screws may fracture due to intrinsic properties of the metal alloy, like hardness, corrosion resistance, and fatigue life. However, the primary causes of fracture are often related to human factors, such as delivering prostheses without achieving passivity, poor adaptation of components, and misuse of the torque wrench (89). As reported in the literature, errors in machining prosthetic screw threads have been verified, leading to grinding of the prosthetic screw socket and early fractures, particularly in the preload. This has raised concerns about the quality of some screws, even within the same brand (100,136). Further analysis may be warranted to understand the specific factors contributing to these observed differences and their implications for clinical practice or product selection.

The results indicate that the torque delivery values of the wrenches were influenced by multiple steam sterilization cycles, with variations observed across different implant brands. This underscores the importance of considering brand-specific factors in the maintenance and calibration of torque wrenches to ensure consistent and accurate torque delivery during implant procedures.

On the other hand, earlier studies that used a direct evaluation method found less deviation from target torque values while the indirect evaluation method showed more deviation. Even though staying within the acceptable 10% range of target torque values in average, outcomes of greater deviations in indirect method highlights the importance of parameters such as material choice of the screw, preload, friction, and settling effect in maintaining desired torque value. Furthermore, the mechanized system employed in this study allowed for precise torque application, minimizing potential operator errors in torque application process. This underscores the importance of standardized procedures and equipment maintenance in achieving reliable outcomes in dental implantology.

This study has several limitations. First, the study focused on four specific implant brands and their cement retained abutments, which may not fully represent the diversity of torque wrenches used in dental implant procedures. Including a broader range of brands could provide a more comprehensive assessment of torque wrench performance. Second, while efforts were made to simulate realistic clinical conditions using a mechanized system, it may not fully replicate the complex oral environment encountered during actual implant procedures. Factors such as temperature variations, saliva and/or blood contamination, and material characteristics could influence torque wrench performance differently than observed in this study. Third, this study opted for an indirect evaluation method, meaning the factors such as material properties of abutment screws, torque wrenches, and abutments might influence the outcome. Furthermore, the parameters such as preload and settling effect are prone to change in value in different situations.

In previous investigations, it has been demonstrated that the preload value diminishes following repeated tightening of the abutment screw. The internal morphology of implants and their response to the settling effect may vary depending on production quality. Utilizing a new implant body for each trial could potentially influence the results and further investigation of potential wear in the internal morphology of dental implants is needed. Last, while the study focused on torque wrench efficacy in a controlled laboratory setting, the clinical relevance of the findings to actual patient outcomes may be uncertain. Further research involving clinical studies and patient outcomes assessment would be necessary to validate the findings in real-world dental practice. Addressing these limitations in future studies would contribute to a more robust understanding of the impact of steam sterilization cycles on torque wrench performance and its implications for dental implant procedures.

In conclusion, our study underscores the critical role of maintenance protocols in ensuring the reliability and accuracy of torque wrenches used in dental implant procedures. The significant impact of multiple steam sterilization cycles on torque delivery values emphasizes the need for regular maintenance and calibration checks. These measures are crucial to mitigate potential discrepancies and ensure optimal treatment outcomes, particularly in the context of long-term implant stability.

One notable finding is the correlation between torque levels and the retention of target torque values. Specimens tested at higher torque levels consistently demonstrated better results in maintaining the desired preload values. This observation suggests that selecting a system that supports higher torque values for screw-retained restorations with single abutment screws can significantly contribute to minimizing screw loosening and enhancing treatment success.

By adhering closely to manufacturer recommendations and implementing rigorous maintenance protocols, dental practitioners can not only enhance the immediate success of implant procedures but also improve the long-term prognosis for patients. These measures not only ensure consistent and reliable outcomes but also contribute to patient satisfaction and overall treatment success rates.

# 6. CONCLUSION

1. All groups were affected by multiple autoclave cycles.
2. Before autoclaving, the most consistent brand in terms of average loosening torque was DTI, with an average of 29.06 N. It was followed by MIS at 28.50 N, NucleOSS at 22.96 N, and NTA, which showed the least consistency with an average loosening torque of 22.71 N.
3. After autoclaving, the most consistent brands in terms of average loosening torque were DTI and MIS, both at 28.59 N. MIS showed slightly more deviation than DTI with 0.13 N. NucleOSS had an average loosening torque of 22.34 N, while NTA showed the lowest value with an average of 21.84 N after autoclaving.
4. MIS exhibited the lowest change after autoclaving, with a maximum of -0,45±4,58% in their trials. DTI followed with 1,45±5,51%, while NucleOSS had a 2,35±8,73% change. The highest change was observed in the NTA group, with 3,41±10,48%.
5. DTI and MIS groups both had the same number of variations with more than a 10% difference from their torque values. Specifically, only 3 of both their trials (7.5%) presented a difference exceeding 10%. Following them, NTA had 12 trials (30%) with more than a 10% range difference from its target torque. The group that demonstrated the most variation was NucleOSS, with 14 of their trials (35%) exceeding the 10% range of their target torque.

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