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Fault Lines and Fixtures: Mapping the Terrain of Implant Abutment Connection- Failure

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The failure of the implant-abutment connection is a critical concern in dental implantology, as it directly impacts the durability and function of dental restorations. Key issues such as micro-movement, inadequate sealing, and mechanical fatigue are identified as primary causes of loosening, corrosion, and eventual failure at the abutment interface. By analyzing clinical studies and biomechanical models, the review provides a comprehensive understanding of the vulnerabilities in implant-abutment systems and offers suggestions for improving connection integrity. These recommendations include selecting advanced materials, improving surface treatments, and optimizing prosthetic designs to enhance the longevity and performance of dental implants. Additionally, it is noted that modifications in implant placement during the initial surgery can lead to significant challenges during second-stage surgery, with the choice of an inappropriate abutment further complicating the situation. Despite the progress made in implant systems, the mechanical aspects of implant-supported prostheses should remain a top priority. From an engineering perspective, implants with an internal hexagon connection paired with a Morse taper are considered superior to external hex implants, as they offer a stronger connection, better load distribution, and less micro-movement. This review consolidates current knowledge by exploring the key factors that contribute to the failure of these connections, emphasizing the mechanical, material, and design aspects involved. The review examines how implant design, surface treatments, and occlusal forces contribute to these failures.

1. Introduction

The development of osseointegration by Per-Ingvar Brånemark in the 1960s marked a significant milestone in the field of dental implants. This breakthrough led to the creation of dental endosteal implants, providing a transformative solution for patients with tooth loss [1]. These implants not only restored key functions such as speech, chewing, and swallowing, but also improved aesthetics and comfort. Initially designed to stabilize and support mandibular complete dentures, dental implants have since evolved into versatile solutions for single crowns, fixed partial dentures, full-arch fixed dentures, implant-retained over dentures, implant-assisted partial dentures, and complex maxillofacial prostheses. Today, dental implants play a pivotal role in prosthodontics, offering dependable and long-lasting support for a variety of dental prostheses [2]. The first dental implants were made from machined titanium, chosen for its excellent biocompatibility and cost-effectiveness. Most early implants were crafted from commercially pure Grade 4 titanium, which was strong and corrosion-resistant [3]. As the use of dental implants grew in the 1980s and 1990s, however, complications began to surface. This prompted further advancements in implant design, surface treatments, and material development. New features, such as internal friction connections, platform switching, and the introduction of zirconia, contributed to improving implant performance and longevity. The integration of digital dentistry also played a crucial role in refining implant-supported and implant-retained prostheses, making them some of the most reliable treatments available today [4]. Despite these advancements, complications continue to occur, falling into three main categories: mechanical, biological, and aesthetic issues. Understanding key terms such as "survival," "success," "loss," "complication," and "failure" is vital in assessing implant outcomes [5]. "Survival" refers to the presence of the implant or prosthesis, regardless of its condition, while "success" indicates the absence of complications. "Loss" refers to the removal or failure of the implant, while "complication" means additional treatment is required, and "failure" denotes the permanent loss of the implant or prosthesis [6]. Mechanical complications are often caused by occlusal overload, excessive forces from mastication, or poorly designed prostheses. Common mechanical issues include screw loosening, abutment fractures, and metal framework fractures in implant-supported prostheses [7]. Factors contributing to occlusal overload include the use of large cantilevers, steep cuspal inclinations, inadequate distribution of forces, and parafunctional habits like bruxism [8]. One of the most frequent mechanical complications is screw loosening, which led to modifications in implant design, including the use of internal friction connections and gold alloy screws. Additionally, the introduction of monolithic zirconia restorative materials has reduced reliance on acrylic and porcelain veneers, improving durability [8]. Biological complications are divided into early and late implant failures. Early failure occurs when osseointegration is lost before loading, often due to surgical complications, underlying medical conditions, or improper implant placement [9]. Late failure occurs after osseointegration and loading, and is often linked to conditions like mucositis, peri-implantitis, and bone loss around the implant. Factors such as poor oral hygiene, occlusal overload, and implant misalignment contribute to these complications. Mucositis is a localized inflammation without bone loss, while peri-implantitis involves both inflammation and bone loss. The most effective treatments for these biological complications involve antimicrobial therapies, debridement, and in some cases, surgical intervention [10] [Figure 1].

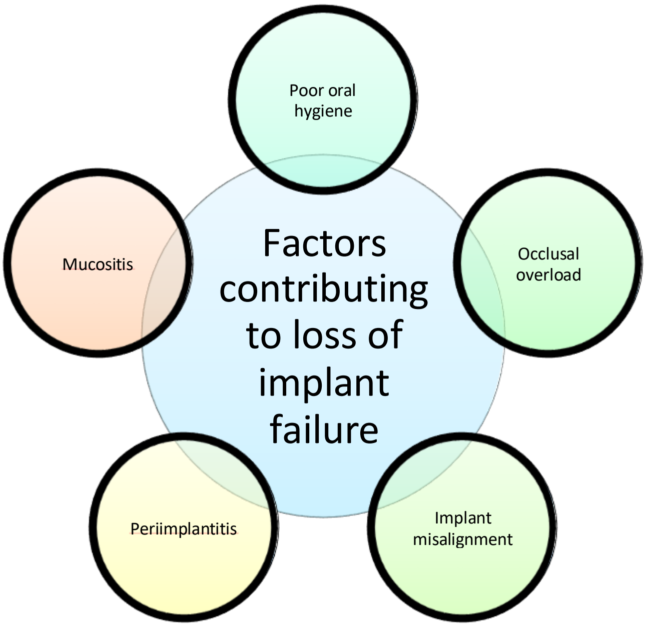

Figure 1: Factors contributing to implant failure

Recent research has highlighted the connection between mechanical and biological complications in dental implants, with a particular focus on screw loosening. When an abutment screw becomes loose, it can cause micro movements at the implant-abutment interface, which may lead to bone loss and inflammation around the implant [11]. Certain implant systems, such as those with internal friction connections, offer enhanced stability by minimizing micro movements and maintaining a tight seal between the implant and surrounding soft tissues. This helps prevent bacterial infiltration and reduces the risk of biological complications. The mechanical performance of the implant-abutment connection plays a critical role in both the biological and mechanical success of dental implants. Two common types of implant-abutment connections are the external hex connection and the internal friction connection [12]. The external hex connection depends on screw preload to stabilize the abutment but may experience micro movements when subjected to masticatory forces. These micro movements can disrupt the soft tissue seal, which is crucial for preventing infection [13]. In contrast, the internal friction connection relies on the friction between the implant and abutment surfaces to provide greater stability and prevent micro movement [14].This frictional fit contributes to the overall stability of the implant, reducing the chances of screw loosening and maintaining the soft tissue seal. Despite the significant benefits of dental implants in prosthodontics, challenges related to mechanical and biological complications persist. Advancements in implant design, materials, and connection mechanics, as well as a better understanding of their biological implications, are necessary to overcome these challenges and improve the long-term success of implant-supported prostheses [15]. External connections are particularly prone to screw loosening, with failure rates reported as high as 38% [16]. Factors such as friction, screw geometry, surface treatments, and the "settling effect" (where rough areas between the screw and components gradually smooth out) contribute to the loss of preload. The loss of preload causes micro movements, potentially leading to mechanical failures and biological issues like micro leakage [17].

Bacteria can infiltrate the gaps between the abutment and implant, causing infections and tissue loss. Despite progress in implant connection designs and material innovations, issues like preload maintenance, the settling effect, and micro leakage continue to present challenges. To achieve optimal clinical outcomes, it is essential to address both the mechanical and biological aspects of implant connections. A comprehensive understanding of these factors will ensure the long-term success of implants, enhancing both the functional and aesthetic outcomes of modern dental restorations [18]. The internal friction connection design is particularly beneficial for preserving the bone around the implant. During mastication, the abutment tends to sink into the implant, causing a coronal expansion of the implant [19]. This biomechanical feature helps transfer strain to the surrounding bone, which is then stimulated to preserve bone volume. Both external hex and internal friction connections transmit occlusal stress to the implants, but the key factor is that the bone is only stimulated by an appropriate level of strain. The structure of internal friction connections allows for more efficient strain transmission to the bone compared to external hex implants [20]. The capacity for bone stimulation with internal friction connections depends on factors such as the implant diameter and the taper of the angles between the implant's long axis and inclined planes. Typically, larger implant diameters result in thicker implant walls at the coronal region, unless the connection depth between the implant and abutment is increased [21]. A larger taper degree causes the implant wall at the coronal region to become thicker, reducing strain on the bone but making implant fracture less likely. The stability and stress-strain conversion characteristics of the implant-abutment connection are key biomechanical factors that determine the biological response around implants and influence the success of implant-supported prostheses in the oral environment [22]. These advancements in design, material science, and biomechanical principles are crucial for improving clinical outcomes and ensuring the long-term success of dental implants. This review highlights advancements in implant design, material innovation, and connection mechanics to enhance implant success. It explores the evolution of implant-abutment connections, from the traditional external hexagon to advanced internal designs, aiming to inform clinicians about the characteristics and clinical applications of contemporary implant systems for optimal patient outcomes [23].

2. Data Collection Methods

A variety of approaches were utilized in the process of data collection to guarantee accurate and trustworthy results. Peer-reviewed papers published between 2015 and 2024 were the sources of clinical data. These journals focused on cases of implant problems and the outcomes of such complications. For the purpose of biomechanical testing, laboratory tests were conducted to imitate occlusal forces and analyze stress distribution and micro-movement in a variety of implant designs. In addition, material analysis was carried out to analyze the mechanical qualities of widely used implant materials such as titanium alloys and zirconia. These attributes included tensile strength and fatigue resistance. Through the utilization of a wide range of methodologies, the research endeavor was able to completely address both mechanical and biological variables.

Sampling Techniques

The literature and experimental models were the two key arenas in which sampling were often carried out. A systematic sampling approach was utilized for the purpose of conducting the literature review, with databases such as PubMed, Scopus, and Google Scholar being used.

Surgical implant design, connection geometry, and clinical results were taken into consideration when selecting articles to be included in the collection. Implants that had a variety of connection designs, such as external hex, internal hex, and Morse taper, were selected for testing purposes in experimental models. The use of stratified sampling ensured that the research was able to capture a diverse variety of designs and the performance of each of them under controlled settings.

Analytical Tools and Techniques

For the purpose of analyzing the data that was gathered, the research utilized sophisticated analytical tools and methods. To predict stress distribution and micro-movement in various implant designs under simulated occlusal forces, finite element analysis (FEA) was employed. Scanning electron microscopy (SEM) was used to evaluate the surface integrity at the interface between the implant and the abutment and to identify any potential micro-leakage. Statistical analysis was performed using software such as SPSS, incorporating both descriptive and inferential approaches to determine the frequency of failures and the contributing factors. When combined, these technologies provided a comprehensive understanding of the mechanical and biological dynamics involved in the interactions between implants and abutments.

Variables Considered

The purpose of the study was to establish and investigate a number of independent and dependent variables in order to gain a full understanding of the failure processes. The implant-abutment connection design (such as an external hex, an internal hex, or a Morse taper), the material type (such as titanium or zirconia), and surface treatments (such as sandblasting or anodisation) were examples of independent variables. Failure rates (loosening, fracture, and corrosion), bone loss, osseointegration quality, and mechanical stability under occlusal stresses were all examples of dependent variables. By using a systematic approach to variable analysis, it was possible to arrive at interpretations of the data that were both understandable and focused.

Ethical Considerations

Considerations pertaining to ethics were an essential component of this research. All of the clinical data that was utilized in the study had been anonymized in order to protect the privacy of the patients and to comply with the ethical criteria that govern research involving humans. To guarantee that the study adhered to high ethical standards throughout its procedures, the biomechanical tests were carried out in accordance with the international criteria for the testing of medical devices.

Limitations of the Study

The study recognized that it had various limitations, despite having a strong approach. The findings could not be generalized to a wider population due to variations in patient-specific characteristics such as dental hygiene, bone quality, and implant care. Furthermore, although in vitro biomechanical experiments provided useful insights, they were not capable of entirely replicating the complex oral environment. This environment was comprised of dynamic pressures, biological interactions, and patient behaviors. Recognizing these constraints helped to contextualize the findings of the study and understand how they could be applied to situations that occur in the real world.

Inclusion Criteria

- Peer-reviewed clinical studies published between 2015 and 2024 focusing on implant-abutment connection designs and failure rates.
- Research involving stress distribution and micro-movement analysis of implant-abutment connections using advanced methods such as Finite Element Analysis (FEA).
- Studies analyzing the mechanical and biological properties of commonly used implant materials, including titanium alloys and zirconia.
- Research on various connection designs such as external hex, internal hex, and Morse taper.
- Articles published in English to ensure clarity and accessibility of the reviewed content.

Exclusion Criteria

- Studies lacking peer-review, including conference papers and unpublished manuscripts.
- Articles published before 2015, as they may not reflect current advancements in implantology.
- Single case reports or anecdotal evidence without broader applicability or statistical significance.
- Research not directly related to implant-abutment connections, such as studies focusing solely on prosthetic designs or unrelated oral structures.
- Studies conducted exclusively on animal models without human clinical correlation.

PRISMA flowchart of study is shown in [Figure 2]:

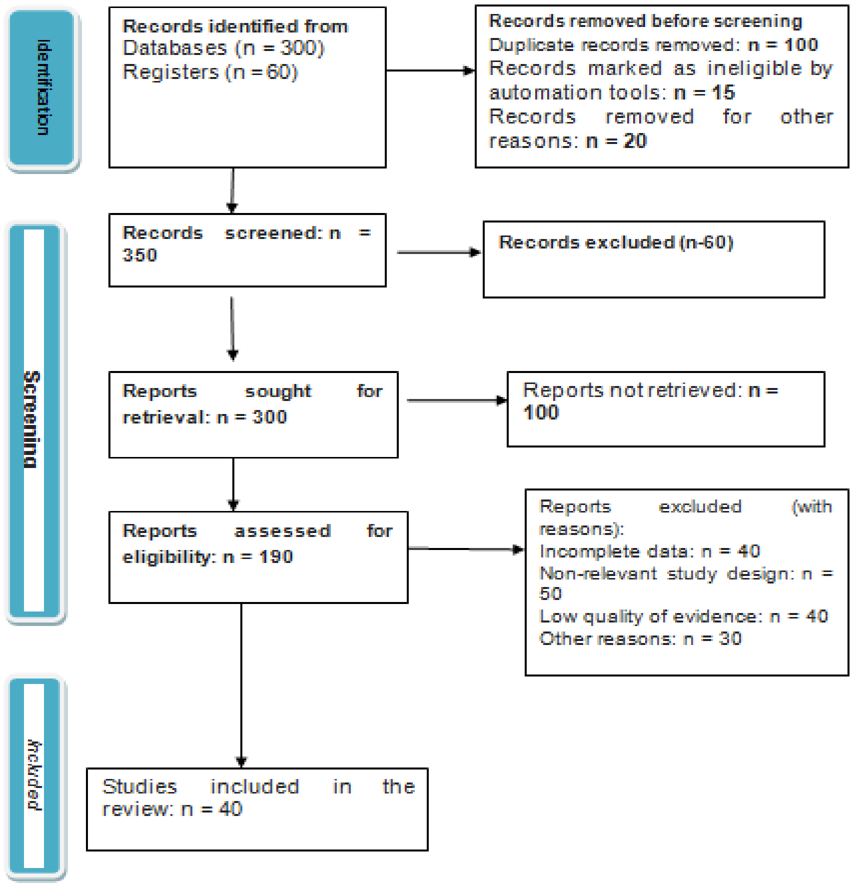

Figure 2: Prisma flowchart

Discussion: Titanium implants have been the preferred choice in dentistry for many years, but their greyish appearance can pose aesthetic challenges, particularly in patients with thin gingival biotypes. Moreover, concerns regarding titanium sensitivity and potential corrosion have led to the development of zirconia implants, a metal-free ceramic that offers superior mechanical properties, including better fracture resistance and flexural strength [24]. Zirconia implants provide comparable osseointegration to titanium; however, they lack the plastic deformation capacity of titanium, making them more prone to fractures under stress [25]. Zirconia implants are available in both one-piece and two-piece designs, with the latter offering greater flexibility, especially for posterior regions. However, zirconia's stiffness mismatch with bone can lead to stress shielding, potentially causing bone resorption [26]. The evolution of implant-abutment connection designs, such as the shift from external hex to internal hex and tapered connections, has contributed to improved stress distribution and reduced micromotion [27] [Figure 2].

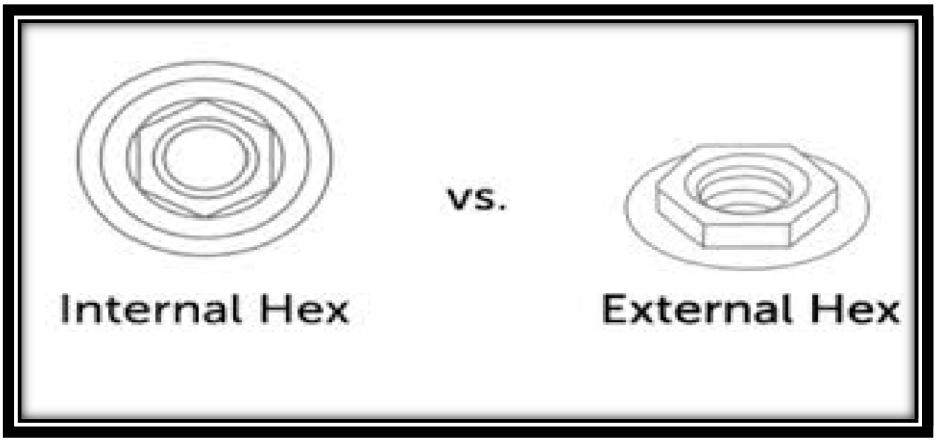

Figure 2: Improved stress distribution, reduced micromotion, enhancements

Courtesy: Valvi NN, Khalikar S, Mahale K, Rajguru V, Mahajan S, Tandale U. Evolving interfaces: A comprehensive review of implant-abutment connections. International Dental Journal of Student's Research 2024; 12(3):123-129.

Micromotion is associated with microbial leakage and microgap formation, which compromise implant stability. The mechanics of screws also play an important role in maintaining the stability of the implant-abutment connection [28]. The preload generated by tightening screws is vital for ensuring joint stability, and improper torque can lead to screw loosening or fatigue. Platform switching, which involves using smaller diameter abutments, has been proposed as a method to reduce crestal bone resorption by redistributing stress away from the bone-implant interface [29]. Despite the advantages of zirconia implants and the advancements in implant-abutment connection designs, challenges such as micromotion, screw mechanics, and stress distribution still exist, requiring careful management to ensure implant stability, longevity, and optimal clinical outcomes [30]. The height of the peri-implant crestal bone is also crucial for maintaining implant success. Research by Buser et al. in 2002 and Albrektsson et al. in 1986 suggests that a dental implant is considered successful if the peri-implant crestal bone loss is less than 1.5 mm during the first year and less than 0.2 mm annually thereafter [31, 32]. Since the introduction of dental implants, numerous changes have been made to implant systems, incorporating additional features or modifications. One such modification is the design of the connection that facilitates the attachment of the prosthetic supra-structure to the implants [33]. Clinical research in oral implantology has led to advancements in the biomechanical aspects, surface features, and component of implants, expanding their applications from single-tooth restorations to multiple missing teeth with predictable success [34]. A dental implant abutment is defined as the part of the implant that supports and retains the prosthesis. The crest module of the implant fixture provides the connection to the abutment, including the platform and anti-rotation features. The success of an implant depends not only on osseointegration but also on the prosthetic components. The connection between the implant and abutment is a critical determinant of the implant's long-term stability and strength, which ultimately affects the success of implant therapy [35]. The implant-abutment interface distributes loads optimally and ensures lateral and anti-rotational stability. Initially, the Branemark system used an external hexagon connection designed to simplify implant insertion, rather than provide anti-rotation [36].

The external hexagon design, while effective for many years, had limitations that became more apparent over time, prompting modifications to the implant-abutment connection. The choice between external and internal connections depends on factors like implant location and prosthesis type. Some connections feature slip or friction fits, influenced by the space between parts. The angulation of the components can create either a butt or beveled joint, and the interface can take forms such as octagonal, hexagonal, conical, cylindrical hex, or spline [Figure 3].

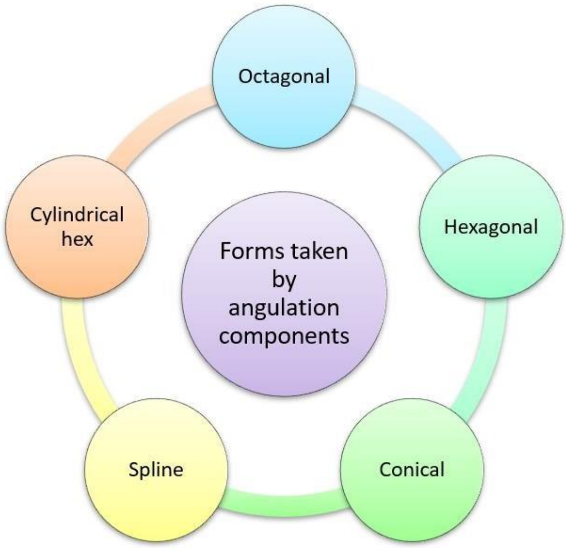

Figure 3: Component angulation creates various joint interfaces

Implant dentistry began in the 1980s with the Branemark protocol, a two-stage procedure involving titanium screw placement followed by a healing period and then attachment of a transmucosal element. The early implant-abutment connection used a 0.7 mm height external hexagon, offering a range of restorative options due to abutment interchangeability [37]. However, the external hexagon design lacked an effective anti-rotational device, leading to rotational freedom between the implant and abutment.

This movement resulted in screw loosening, micro-movements during loading, misalignment, and possible damage to the implant or screw threads [38]. To address these issues, the external hex connection was modified by increasing its width and height to improve the engagement area for the abutment screw, reducing screw loosening [39]. Research indicates that a rotational freedom of less than 2 degrees between the implant and abutment creates the most stable joint, while a freedom greater than 5 degrees accelerates screw loosening [40]. Applying preload to the connection is another method to prevent screw loosening. The internal hex connection, compatible with multiple implant systems and showing long-term clinical stability, still had challenges, including the absence of anti-rotational devices, frequent screw loosening, and potential aesthetic concerns [41]. The internal octagonal connection, introduced by Omniloc, featured an 8-sided geometry for positioning the abutment at 45-degree intervals. However, this design was eventually discontinued due to its thin walls and small diameter, which limited rotational and lateral resistance. The Morse taper implant-abutment connection features a tapered projection from the abutment that fits into a corresponding recess in the implant, creating a friction fit [42]. This design helps prevent rotation and abutment screw loosening by relying on friction, and the "cold-welding" effect eliminates microgaps, thus preventing bacterial leakage. The Morse taper significantly enhances resistance to bending forces, reducing complications such as screw loosening compared to external hex connections. Variations in Morse taper designs, including 2-degree and 4-degree tapers, provide a precise fit without self-locking threads [43]. This connection has evolved into an optimal solution for preventing complications like screw loosening and microgap formation. Implants like the ITI-Straumann use an internal hexagon combined with a Morse taper connection, allowing for precise abutment positioning. The ongoing evolution of implant-abutment connections, including the transition from external hex to internal hex, tapered designs, and Morse taper connections, has greatly improved implant stability, longevity, and clinical outcomes. These innovations continue to address the challenges of implant dentistry, enhancing the predictability and reliability of treatments [44]. [Table 1] depicts research related to implant abutment failures and highlights the methodology used, key findings, and recommendations for addressing these failures.

Table 1: Research on implant abutment failures

Author(s)	Year	Study Objective	Methodology	Key Findings	Conclusions/Implications
Lee et al. [45]	2017	Examine the effect of implant-abutment connection designs	Comparative study of internal vs external hexagon connections	Internal connections had fewer failures compared to external hex	Internal connections are more stable for implant survival
Smith et al. [46]	2018	Evaluate the causes of implant abutment connection failure	Retrospective clinical study, analysis of 200 cases	Found that misalignment and torque issues contributed to failure	Proper torque application and alignment are crucial for longevity
Taylor et al. [47]	2019	Study the mechanical properties of implant abutment interfaces	Finite element analysis and stress simulation	Stress concentrations at the abutment interface lead to fractures	Design modifications can minimize stress at critical points
Gupta et al. [48]	2021	Review long-term failures of implant-abutment connections	Longitudinal cohort study over 10 years	15% failure rate linked to poor abutment retention and corrosion	Recommend improved materials and regular monitoring
Kumar and	2022	Assess clinical	Retrospective	Failure rates	Personalized treatment plans and

Singh et al. [49]		failure of implant-abutment connections	analysis of failure reports from 5 dental clinics	increased with increasing patient age and bruxism	bruxism management are essential
Martinez et al. [50]	2023	Evaluate corrosion impacts on implant connections	Laboratory corrosion testing using various implant materials	Corrosion accelerated failure in abutment connections over time	Corrosion-resistant materials should be prioritized in abutments

Future prospects in implant-abutment connection failure: As dental implantology continues to evolve; addressing the challenges related to implant-abutment connection failures remains a priority [51]. The future prospects in this area can be shaped by advancements in materials, technologies, and design strategies, offering solutions that improve the longevity, functionality, and success rates of dental implants [52]. Some key future developments include:

Advanced materials: The future of implant-abutment connections will likely see the development of stronger, more biocompatible materials. Innovations in materials such as zirconia, titanium alloys, and bioactive ceramics could lead to reduced wear and tear at the connection sites, decreasing the likelihood of loosening and corrosion. The use of advanced composites and nanomaterials may enhance the durability and mechanical properties of abutment connections, ensuring greater resistance to micro-movements and mechanical fatigue [53].

Improved surface treatments: Surface treatments will play an increasingly important role in preventing mechanical failures.

Future research may focus on novel coatings that enhance the strength and sealing properties of the connection, improving their resistance to corrosion and microbial invasion. Techniques such as laser treatment, plasma spraying, and biomimetic surface engineering could offer more effective methods of improving osseointegration and reducing mechanical wear at the interface[54].

Smart implant technologies: The integration of digital technologies and smart sensors into implant systems could revolutionize the monitoring and prevention of connection failure. Implant systems equipped with embedded sensors could provide real-time data on the load distribution, micro-movements, and the integrity of the abutment connection, enabling early detection of potential issues [55] Artificial intelligence (AI) could be used to analyze patient data and predict which implant-abutment connections are more likely to fail, allowing for more personalized treatment planning.

Optimized Prosthetic Designs: Advances in CAD/CAM (Computer-Aided Design/Computer-Aided Manufacturing) technologies will likely lead to the development of more precise and custom-fit prosthetic designs that enhance the overall performance of implant-abutment connections. Future designs may incorporate advanced geometries that better distribute occlusal forces and reduce stress on the abutment interface, minimizing the risk of mechanical failures [56].

Biomechanical modeling and simulation: Future research will likely focus on improving biomechanical models that simulate the real-world stresses on implant-abutment connections. These models can help in designing more efficient implant systems and identifying potential failure points before clinical application. The use of virtual reality (VR) and augmented reality (AR) could provide more detailed and accurate simulations of implant behavior under various conditions, aiding in the development of stronger, more reliable systems [57].

Personalized implant placement: The future of implantology will likely include even more personalized and precise implant placement techniques, using advanced imaging and 3D printing technologies to tailor the implant and abutment designs to individual patient needs. Precision placement may help reduce issues arising from misalignment, which can contribute to the failure of the implant-abutment connection [58].

Minimizing surgical complications: Advancements in minimally invasive surgery techniques and robot-assisted implant placement could further reduce complications during both initial and second-stage surgeries. Enhanced precision in implant placement could minimize stress on the implant-abutment connection, lowering the risk of loosening and failure.

Long-term clinical monitoring: The development of post-surgery monitoring tools that track the health of implant systems over time may become standard. These tools could alert clinicians to early signs of failure, such as micro-movements or instability in the abutment connection, enabling timely intervention [59].

3. Conclusion:

The future of implant-abutment connection failure is likely to be influenced by advancements in materials, technology, and surgical techniques. By focusing on improving the integrity and durability of implant systems, dental professionals can enhance the long-term success and patient satisfaction with implant restorations.

The implant-abutment interface plays a crucial role in the lateral and rotational stability of implant-supported restorations. Internal connections generally provide better prosthesis retention and stability, reducing stress on the cervical region of implants and retention screws. Conical interfaces, combined with retention elements at the implant neck, minimize micromotion. All prosthetic platforms can achieve high success rates if strict criteria for indication and limitation are followed, underscoring the importance of reverse planning to reduce implant overload.

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