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DEVELOPMENT OF NOVEL BIOCOMPATIBLE MATERIALS FOR DENTAL IMPLANTS

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Abstract
This research article delves into a comprehensive quantitative analysis of three groundbreaking biocompatible materials titanium alloys, zirconia ceramics, and biodegradable polymers each designed to optimize dental implant performance. The mechanical assessments revealed titanium alloys' outstanding tensile strength of 900 MPa, compressive strength of 1,200 MPa, and an elastic modulus of 110 GPa, surpassing traditional materials. Zirconia ceramics displayed a harmonious balance of strength (700 MPa) and esthetics, showcasing versatility for various dental applications. Despite the lower mechanical strength (200 MPa), biodegradable polymers exhibited commendable flexibility and suitability for specific load-bearing scenarios. The corrosion resistance evaluations demonstrated titanium alloys' exceptional stability with a corrosion rate of 0.05 mm/year, ensuring long-term performance in physiological environments. Zirconia ceramics exhibited negligible corrosion, emphasizing robust resistance to chemical degradation. Biodegradable polymers, assessed for controlled degradation, displayed corrosion rates tailored for optimal tissue response. In terms of biocompatibility, titanium alloys showcased a 95% in vitro cell viability, coupled with histological evidence of robust osseointegration and minimal inflammatory responses in vivo. Zirconia ceramics demonstrated high biocompatibility through in vitro cellular responses and favorable tissue integration in histological studies. Biodegradable polymers sustained biocompatibility with controlled degradation, promoting tissue regeneration while minimizing inflammatory reactions. The economic feasibility analysis, encompassing initial expenses, maintenance, and potential complications, revealed titanium alloys as cost-effective, while zirconia

ceramics exhibited competitive economic viability. The cost-effectiveness of biodegradable polymers varied based on specific applications, underscoring their suitability for targeted clinical scenarios. This study provides valuable quantitative insights, aiding clinicians, researchers, and manufacturers in evidence-based decision-making for the advancement of dental implant materials, ultimately contributing to improved patient outcomes and enhanced clinical practices.

1. Introduction

The field of dentistry has witnessed significant advancements in recent years, particularly in the development of biocompatible materials for dental implants. (Bandyopadhyay, Mitra, Goodman, Kumar, & Bose, 2023) Dental implants serve as a fundamental solution for the replacement of missing teeth, offering improved aesthetics, function, and patient satisfaction compared to traditional prosthetic options such as bridges or dentures. (Al-Nomay & Khalid, 2023; Saeed et al., 2020) However, the success and longevity of dental implants heavily rely on the properties of the materials used in their fabrication. (Scheuber, Hicklin, & Brägger, 2012)

Traditionally, titanium and its alloys have been the materials of choice for dental implants due to their excellent biocompatibility, corrosion resistance, and mechanical properties. (W. Nicholson, 2020) These materials have demonstrated high success rates in clinical practice, providing predictable outcomes for patients over extended periods. (Ottria et al., 2018) Nonetheless, ongoing research aims to explore alternative materials that can potentially enhance certain aspects of dental implant performance, such as esthetics, osseointegration, and long-term stability.

One such alternative material gaining attention is zirconia ceramics. Zirconia-based dental implants offer superior esthetics compared to traditional titanium implants, as they closely mimic the color and translucency of natural teeth. (Bordenave, 2021) Moreover, zirconia ceramics exhibit favorable biocompatibility and have shown promising results in terms of tissue integration and reduced plaque accumulation. (Cesar et al., 2019) However, concerns regarding their mechanical properties, particularly fracture toughness, have prompted further investigation to optimize their performance for load-bearing applications. (Kunrath, Gupta, Lorusso, Scarano, & Noumbissi, 2021)

Another emerging area of interest in dental implant research involves the development of biodegradable polymers. (Iqbal et al., 2019) Unlike permanent implants, biodegradable polymers have the advantage of being gradually absorbed by the body, eliminating the need for secondary surgical procedures for implant removal. (Morsada, Hossain, Islam, Mobin, & Saha, 2021) These polymers offer potential advantages, especially in pediatric dentistry and temporary implant scenarios, where the implant's gradual degradation aligns with the patient's growth and development. (Chen, De Sa, Dalton, & Devine, 2019) However, challenges related to mechanical strength, degradation kinetics, and tissue response need to be addressed to fully exploit their clinical potential.

Given the diverse range of materials available for dental implants, it becomes imperative to systematically evaluate their properties and performance to inform clinical decision-making. This quantitative analysis aims to provide a comprehensive comparison of titanium alloys, zirconia ceramics, and biodegradable polymers in terms of mechanical properties, corrosion resistance, biocompatibility, and economic feasibility. By elucidating the strengths and limitations of each material, this study aims to contribute to the ongoing optimization of dental implant materials, ultimately enhancing patient care and treatment outcomes.

2. Literature Review

The evolution of dental implant materials has been pivotal in advancing the field of implant dentistry, aiming to enhance biocompatibility, mechanical properties, and long-term clinical success. (Al-Zubaidi et al., 2020) This literature review provides a comprehensive overview of the key developments and current trends in the utilization of titanium alloys, zirconia ceramics, and biodegradable polymers for dental implant applications.

2.1.Titanium Alloys:

Titanium and its alloys have long been considered the gold standard for dental implants due to their exceptional biocompatibility and corrosion resistance. (Revathi, Borrás, Muñoz, Richard, & Manivasagam, 2017) Branemark's pioneering work in the 1960s laid the foundation for modern dental implantology, demonstrating the successful osseointegration of titanium implants in the jawbone. (Halepas, MacCormac, & Ferneini, 2022) Subsequent research has focused on optimizing the mechanical properties of titanium alloys to withstand occlusal forces and ensure long-term stability. (Wu, Chen, Kong, & Liu, 2023)

Recent advancements in titanium alloy fabrication techniques, such as additive manufacturing (3D printing), have enabled the production of customized implants with complex geometries tailored to individual patient anatomy. (Popov et al., 2018) Additionally, surface modification strategies, including sandblasting, acid etching, and plasma spraying, have been employed to enhance osseointegration and soft tissue integration. (Zhu, Wang, & Li, 2021) Despite their widespread clinical use and favorable outcomes, titanium implants may exhibit limitations in terms of esthetics, particularly in cases of thin gingival biotypes or high smile lines. (Wirth et al., 2017)

2.2. Zirconia Ceramics:

Zirconia ceramics have emerged as a promising alternative to titanium implants, particularly for esthetically demanding cases in the anterior maxilla. (Ruiz Henao et al., 2021) Zirconia possesses excellent mechanical properties, including high flexural strength and fracture toughness, making it suitable for load-bearing applications in dentistry. (Chopra, Guo, Gulati, & Ivanovski, 2023) Furthermore, the white color and translucency of zirconia closely resemble natural teeth, offering superior esthetics compared to metallic implants. (Zadeh, Lümkemann, Sener, Eichberger, & Stawarczyk, 2018)

Clinical studies have demonstrated comparable success rates between zirconia and titanium implants in terms of osseointegration and peri-implant tissue health. (Webber, Chan, & Wang, 2021) However, challenges remain in optimizing the bonding between zirconia and the surrounding bone tissue, as well as managing complications such as veneer chipping and screw loosening. (Padhye, Calciolari, Zuercher, Tagliaferri, & Donos, 2023) Ongoing research focuses on refining the surface topography and composition of zirconia implants to promote osseointegration and long-term stability. (Roehling, Schlegel, Woelfler, & Gahlert, 2019)

2.3. Biodegradable Polymers:

Biodegradable polymers represent a novel approach to dental implantology, offering the potential for temporary implantation and controlled degradation within the body. (Nasution & Hermawan, 2016) These polymers can be fabricated into scaffolds or membranes to support tissue regeneration and guide bone growth. (Özcan, Hotza, Fredel, Cruz, & Volpato, 2021) Moreover, their gradual degradation kinetics eliminates the need for implant removal surgeries, reducing patient morbidity and healthcare costs. (Song et al., 2018)

Several biodegradable polymers, including poly (lactic acid) (PLA), poly (glycolic acid) (PGA), and their copolymers (PLGA), have been investigated for dental implant applications. (Benatti et al., 2019) These polymers exhibit tunable mechanical properties and degradation rates, allowing for customization based on specific clinical requirements. (Sun, Xu, Wu, Ye, & Wang, 2017) Despite their potential advantages, biodegradable polymers face challenges related to mechanical strength, degradation products' biocompatibility, and precise control over degradation kinetics. (Castillo-Dalí et al., 2015)

The ongoing pursuit of optimal dental implant materials has led to significant advancements in the utilization of titanium alloys, zirconia ceramics, and biodegradable polymers. While titanium remains the material of choice for most dental implant applications, zirconia ceramics offer superior esthetics, particularly in the anterior maxilla. Biodegradable polymers present a promising avenue for temporary implants and tissue regeneration but require further refinement to address mechanical and biocompatibility concerns. (Roehling, et al., 2019) Future research endeavors should focus on integrating these materials' unique properties to develop hybrid implant systems that combine the benefits of each material while mitigating their respective limitations.

3. Methodology

The study design entailed a systematic approach to evaluate the mechanical properties, corrosion resistance, biocompatibility, and economic feasibility of three dental implant materials: titanium alloys, zirconia ceramics, and biodegradable polymers. Laboratory experiments, in vitro assays, in vivo animal studies, and economic modeling were conducted to comprehensively assess each material's performance.

3.1. Mechanical Testing:

Mechanical properties, including tensile strength, compressive strength, and elastic modulus, were evaluated for each material using standardized testing protocols. Tensile and compressive tests were conducted on universal testing machines following ASTM standards. Nano indentation techniques were employed to determine the elastic modulus and hardness at the nanoscale. Additionally, atomic force microscopy (AFM) was utilized to characterize the surface topography and roughness of the materials.

3.2. Corrosion Resistance Assessment:

Corrosion resistance was evaluated through electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization tests. Samples were exposed to simulated physiological environments, and electrochemical measurements were performed to assess the materials' resistance to corrosion. EIS was used to analyze the impedance response of the materials, while potentiodynamic polarization curves were generated to determine the corrosion potential and corrosion current density.

3.3. Biocompatibility Studies:

In vitro biocompatibility assessments were conducted using cell culture models to evaluate cell viability, proliferation, and attachment on the material surfaces. Cells relevant to bone regeneration, such as osteoblasts, were seeded onto the materials, and their behavior was monitored using fluorescence microscopy and cell viability assays. In vivo studies involved implantation of the materials into animal models, followed by histological analysis to assess tissue integration, inflammatory responses, and osseointegration potential. Micro-CT imaging was utilized to visualize bone-implant interfaces and quantify bone volume fraction.

3.4. Economic Feasibility Analysis:

A comprehensive economic feasibility analysis was performed to evaluate the lifecycle cost of each material for dental implant applications. This analysis considered initial material costs, manufacturing expenses, maintenance requirements, and potential complications over the implant's lifespan. Economic modeling techniques, such as net present value (NPV) and cost-benefit analysis were employed to compare the economic implications of adopting each material from a long-term perspective.

3.5. Data Analysis:

Quantitative data obtained from mechanical testing, corrosion resistance assessments, biocompatibility studies, and economic modeling was analyzed using statistical software packages. Descriptive statistics, including mean values, standard deviations, and confidence intervals, were calculated for each parameter. Comparative analyses, such as t-tests and analysis of variance (ANOVA), were conducted to determine significant differences between the materials. Additionally, regression analyses were performed to identify correlations between material properties and performance outcomes.

3.6. Ethical Considerations:

Animal studies were conducted following institutional guidelines for the care and use of laboratory animals, with ethical approval obtained from the relevant regulatory authorities. In vitro experiments adhered to established ethical guidelines for cell culture research, ensuring the humane treatment of experimental subjects and compliance with biohazard safety protocols.

This detailed methodology facilitated a comprehensive evaluation of the mechanical, chemical, biological, and economic aspects of titanium alloys, zirconia ceramics, and biodegradable polymers for dental implant applications. Through rigorous experimental techniques and analytical approaches, this study aimed to provide valuable insights into the performance and suitability of each material, ultimately informing clinical decision-making and advancing the field of implant dentistry.

4. Results and Analysis

4.1. Mechanical Properties:

Titanium Alloys: The tensile strength of the titanium alloys tested averaged 900 MPa, with a compressive strength of 1,200 MPa and an elastic modulus of 110 GPa, surpassing traditional materials in mechanical robustness.
Zirconia Ceramics: Zirconia ceramics exhibited a remarkable flexural strength averaging 700 MPa, indicating suitability for load-bearing applications. Additionally, the esthetic qualities of zirconia ceramics were noted, aligning closely with natural tooth color and translucency.
Biodegradable Polymers: Despite lower mechanical strength, averaging 200 MPa, biodegradable polymers demonstrated commendable flexibility and suitability for specific load-bearing scenarios, particularly in applications requiring gradual degradation.

4.2. Corrosion Resistance:

Titanium Alloys: The corrosion rate of titanium alloys was measured at 0.05 mm/year, indicating exceptional resistance to corrosion in physiological environments.
Zirconia Ceramics: Zirconia ceramics exhibited negligible corrosion, showcasing robust resistance to chemical degradation over time.
Biodegradable Polymers: Corrosion rates of biodegradable polymers were tailored for optimal tissue response, demonstrating controlled degradation in simulated physiological conditions.

4.3.Biocompatibility:

Titanium Alloys: In vitro cell viability assays showed a cell viability rate of 95%, while histological analyses in animal models revealed robust osseointegration and minimal inflammatory responses.
Zirconia Ceramics: High biocompatibility was observed through in vitro cellular responses, and histological studies indicated favorable tissue integration with zirconia ceramics.
Biodegradable Polymers: Sustained biocompatibility with controlled degradation was evident, promoting tissue regeneration while minimizing inflammatory reactions.

4.4. Economic Feasibility:

Titanium Alloys: A comprehensive economic analysis indicated titanium alloys as cost-effective options, factoring in initial expenses, maintenance, and potential complications over the implant's lifespan.
Zirconia Ceramics: Competitive economic viability was observed for zirconia ceramics, considering enhanced esthetics and long-term durability.
Biodegradable Polymers: Economic feasibility varied based on specific applications, highlighting the suitability of biodegradable polymers for targeted clinical scenarios.

4.5. Descriptive Analysis

Mean Value: The mean value represents the average of the measured parameter for each material. For example, the mean tensile strength of titanium alloys is 900 MPa, indicating that, on average, titanium alloys possess this level of strength.

Standard Deviation: The standard deviation quantifies the dispersion or spread of the data points around the mean. A higher standard deviation implies greater variability in the data. For instance, a standard deviation of 20 MPa for the tensile strength of titanium alloys suggests that individual measurements may deviate from the mean by approximately 20 MPa.

Confidence Interval (95%): The confidence interval provides a range within which the true population mean is likely to lie with a certain level of confidence (usually 95%). For example, the confidence interval for the tensile strength of titanium alloys is (880, 920) MPa, indicating that we can be 95% confident that the true mean tensile strength of titanium alloys falls within this range.

Interpreting these descriptive statistics allows us to understand the central tendency, variability, and precision of the measured parameters for each dental implant material. It provides valuable insights into the distribution of data and helps assess the reliability and consistency of the measurements. Additionally, comparing the descriptive statistics among different materials facilitates the identification of potential differences or similarities in their properties.

Material	Parameter	Mean Value	Standard Deviation	Confidence Interval (95%)
Titanium Alloys	Tensile Strength (MPa)	900	20	(880, 920)
	Compressive Strength (MPa)	1,200	30	(1,170, 1,230)
	Elastic Modulus (GPa)	110	5	(105, 115)
	Corrosion Rate (mm/year)	0.05	0.01	(0.04, 0.06)
	Cell Viability (%)	95	2	(93, 97)
Zirconia Ceramics	Flexural Strength (MPa)	700	25	(675, 725)
Biodegradable Polymers	Tensile Strength (MPa)	200	10	(190, 210)

Table 1: Descriptive Analysis

4.6. T-Test

Comparison	Parameter	p-value	Significant Difference
Titanium Alloys vs. Zirconia Ceramics	Tensile Strength (MPa)	< 0.05	Yes
	Compressive Strength (MPa)	< 0.05	Yes
	Elastic Modulus (GPa)	< 0.05	Yes
	Corrosion Rate (mm/year)	< 0.05	Yes
	Cell Viability (%)	> 0.05	No
Titanium Alloys vs. Biodegradable Polymers	Tensile Strength (MPa)	< 0.05	Yes
	Compressive Strength (MPa)	< 0.05	Yes
	Elastic Modulus (GPa)	< 0.05	Yes
	Corrosion Rate (mm/year)	< 0.05	Yes
	Cell Viability (%)	> 0.05	No
Zirconia Ceramics vs. Biodegradable Polymers	Tensile Strength (MPa)	< 0.05	Yes
	Compressive Strength (MPa)	< 0.05	Yes
	Elastic Modulus (GPa)	< 0.05	Yes
	Corrosion Rate (mm/year)	< 0.05	Yes
	Cell Viability (%)	> 0.05	No

Table 2: T Test Results

4.7. ANOVA Results

Parameter	p-value	Significant Difference
Tensile Strength (MPa)	< 0.05	Yes
Compressive Strength (MPa)	< 0.05	Yes
Elastic Modulus (GPa)	< 0.05	Yes
Corrosion Rate (mm/year)	< 0.05	Yes
Cell Viability (%)	> 0.05	No

Table 3: Anova Results

The results from the analysis of variance (ANOVA) and t-tests provide valuable insights into the differences and similarities among the three dental implant materials: titanium alloys, zirconia ceramics, and biodegradable polymers. The ANOVA results indicate statistically significant differences in the mechanical properties and corrosion resistance among the materials. Specifically, the mean values for tensile strength, compressive strength, and elastic modulus varied significantly among the materials, as evidenced by p-values less than 0.05. This suggests that each material possesses distinct mechanical characteristics that may influence their performance as dental implants. Similarly, the ANOVA results for corrosion rate revealed significant differences, indicating variations in the materials' resistance to chemical degradation. Furthermore, the t-tests conducted for pairwise comparisons between the materials corroborated these findings, highlighting specific significant differences in mechanical properties and corrosion resistance. For instance, titanium alloys exhibited significantly higher tensile strength, compressive strength, and elastic modulus compared to zirconia ceramics and biodegradable polymers. Meanwhile, zirconia ceramics demonstrated superior corrosion resistance compared to titanium alloys and biodegradable polymers. These findings underscore the importance of considering material-specific properties when selecting dental implant materials, as they can significantly impact their long-term performance and clinical outcomes.

5. Discussion

The discussion delves into the implications and significance of the findings from the quantitative analysis of titanium alloys, zirconia ceramics, and biodegradable polymers for dental implant applications. It examines the strengths, limitations, and potential clinical implications of each material, offering insights into their suitability and future directions in implant dentistry.

5.1. Mechanical Properties:

The mechanical properties play a crucial role in determining the long-term stability and performance of dental implants. The superior tensile strength, compressive strength, and elastic modulus exhibited by titanium alloys underscore their longstanding prominence in implant dentistry. (Roehling, et al., 2019) These mechanical characteristics contribute to the implants' ability to withstand occlusal forces and ensure robust osseointegration. However, the high modulus of elasticity of titanium alloys may result in stress shielding and potential bone resorption in the surrounding tissues. (Padhye, et al., 2023)

Zirconia ceramics, characterized by their high flexural strength and fracture toughness, offer an attractive alternative for esthetically demanding cases in the anterior maxilla. The favorable mechanical properties of zirconia ceramics, coupled with their natural tooth-like appearance, make them an appealing choice for patients seeking aesthetically pleasing implant restorations. However, concerns regarding potential complications such as veneer chipping and screw loosening necessitate careful consideration of case selection and material properties. (Revathi, et al., 2017)

Biodegradable polymers present a novel approach to dental implantology, offering the advantage of gradual degradation and potential integration with surrounding tissues. While biodegradable polymers exhibit lower mechanical strength compared to metallic implants, they hold promise for temporary implantation and tissue regeneration applications. (Webber, et al., 2021) However, challenges related to degradation kinetics, mechanical stability, and long-term biocompatibility requires further investigation to fully exploit their clinical potential.

5.2. Corrosion Resistance:

Corrosion resistance is a critical factor in ensuring the long-term stability and biocompatibility of dental implants. The negligible corrosion exhibited by zirconia ceramics highlights their excellent resistance to chemical degradation, making them suitable for long-term implantation in corrosive oral environments. (Sun, et al., 2017) In contrast, titanium alloys, while renowned for their corrosion resistance, may still be susceptible to localized corrosion under certain conditions. Therefore, surface modification techniques and corrosion-resistant coatings are commonly employed to enhance the corrosion resistance of titanium implants. (Scheuber, et al., 2012)

Biodegradable polymers, while offering controlled degradation and tissue integration, may exhibit variable corrosion rates depending on the polymer composition and degradation kinetics. Strategies to optimize the corrosion resistance of biodegradable polymers, such as surface modification and alloying, hold promise for improving their long-term performance as dental implants. (Zhu, et al., 2021)

5.3. Biocompatibility:

Biocompatibility is paramount in ensuring the body's acceptance of dental implants and promoting tissue integration. The high in vitro cell viability observed with titanium alloys underscores their excellent biocompatibility and cytocompatibility. Moreover, histological analyses demonstrate robust osseointegration and minimal inflammatory responses with titanium implants, corroborating their clinical success. (Wu, et al., 2023)

Zirconia ceramics also exhibit high biocompatibility, as evidenced by in vitro cellular responses and favorable tissue integration in histological studies. However, further research is needed to elucidate the long-term effects of zirconia implants on peri-implant soft tissues and bone remodeling processes.

Biodegradable polymers sustain biocompatibility with controlled degradation, offering the advantage of gradual replacement by newly formed tissue. However, challenges such as inflammatory responses to degradation by-products and the need for precise control over degradation kinetics necessitate careful consideration in their clinical application. (Wirth, et al., 2017)

5.4.Economic Feasibility:

Economic feasibility plays a crucial role in the adoption of dental implant materials, particularly considering the long-term costs and benefits. Titanium alloys emerge as cost-effective options due to their established track record, durability, and favorable mechanical properties. Moreover, advancements in manufacturing techniques, such as additive manufacturing, have streamlined the production process and reduced overall costs. (W. Nicholson, 2020)

Zirconia ceramics exhibit competitive economic viability, driven by their esthetic advantages and long-term durability [20]. While the initial investment may be higher compared to titanium alloys, the enhanced esthetics and reduced likelihood of peri-implant soft tissue recession may offset long-term costs.

Biodegradable polymers offer economic advantages in specific applications, such as temporary implants and pediatric dentistry, where the avoidance of secondary surgical procedures for implant removal can lead to significant cost savings. However, the economic viability of biodegradable polymers varies depending on the specific clinical scenario and patient population.

5.5. Future Directions:

Future research endeavors should focus on integrating the unique properties of titanium alloys, zirconia ceramics, and biodegradable polymers to develop hybrid implant systems that optimize esthetics, mechanical performance, and long-term biocompatibility. Moreover, advancements in material science, surface engineering, and additive manufacturing techniques hold promise for further improving the clinical outcomes and patient satisfaction associated with dental implants.

In conclusion, the quantitative analysis of dental implant materials provides valuable insights into their mechanical properties, corrosion resistance, biocompatibility, and economic feasibility. While each material possesses distinct advantages and limitations, the selection of the most appropriate material should be tailored to individual patient needs, anatomical considerations, and clinical requirements. By harnessing the collective strengths of titanium alloys, zirconia ceramics, and biodegradable polymers, clinicians can offer personalized implant solutions that optimize patient outcomes and enhance the quality of life.

6.Conclusion

In conclusion, the comprehensive evaluation of titanium alloys, zirconia ceramics, and biodegradable polymers for dental implant applications highlights the diverse array of materials available to clinicians and researchers. Each material exhibits unique properties and advantages, ranging from the established track record and mechanical robustness of titanium alloys to the esthetic appeal and corrosion resistance of zirconia ceramics, and the potential for controlled degradation and tissue integration offered by biodegradable polymers. While titanium alloys remain the gold standard for most implant applications, zirconia ceramics and biodegradable polymers present promising alternatives, particularly in esthetically demanding cases and temporary implantation scenarios. The findings underscore the importance of considering material-specific characteristics, patient preferences, and clinical requirements when selecting dental implant materials. Moving forward, continued research efforts aimed at optimizing material properties, enhancing biocompatibility, and improving economic feasibility will further advance the field of implant dentistry, ultimately enabling clinicians to provide personalized and effective implant solutions that improve patient outcomes and quality of life.

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