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To Compare and Evaluate the Color Stability of Intrinsically Stained Artificially Aged Two Different Heat Polymerized Maxillofacial Silicone Elastomers by Addition of Zirconium Dioxide and Titanium Dioxide Nanoparticles - An In-Vitro Study

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Abstract:

- ***Background:***

Color stability is essential for the longevity and esthetic success of maxillofacial silicone prostheses. Heat-polymerized silicone elastomers are prone to discoloration following environmental exposure. Ultraviolet protective nanoparticles have been proposed to improve their optical stability.

- ***Aim:***

To compare the color stability of two intrinsically stained heat-polymerized maxillofacial silicone elastomers reinforced with zirconium dioxide (ZrO_2) and titanium dioxide (TiO_2) nanoparticles following artificial aging.

- ***Materials and Methods:***

An in vitro study was conducted using 120 disc-shaped specimens (20 mm × 3 mm) fabricated from Technovent and MP Sai heat-polymerized silicone elastomers. Specimens were allocated into six groups (n = 20), with ZrO_2 and TiO_2 nanoparticles incorporated before polymerization. Artificial aging was performed according to ASTM G154 Cycle 1. Color measurements were recorded at baseline and after 252, 504, and 1008 hours using a digital spectrophotometer based on the CIELAB system. Data were analyzed using one-way ANOVA, repeated-measures ANOVA, and Tukey's post hoc test ($p < 0.05$).

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➢ ***Results:***

Artificial aging caused progressive discoloration in all groups. Control specimens showed the highest ΔE values, with MP Sai control exhibiting the greatest color change (3.78 ± 0.10). Nanoparticle reinforcement significantly improved color stability ($p < 0.001$). TiO_2-reinforced specimens demonstrated lower ΔE values than ZrO_2-reinforced specimens, with Technovent + TiO_2 showing the best color stability (1.32 ± 0.05).

➢ ***Conclusion:***

Incorporation of nanoparticles significantly improved the color stability of heat-polymerized maxillofacial silicone elastomers after artificial aging. TiO_2 provided superior protection against discoloration, while Technovent silicone demonstrated better overall color stability than MP Sai silicone.

Keywords: *Color Stability, Maxillofacial Silicone, Digital Colorimeter, Artificial Aging.*

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I. INTRODUCTION

Maxillofacial prosthetic rehabilitation plays a critical role in restoring facial form and function in patients affected by congenital deformities, trauma, infection, or oncologic resection. Beyond functional restoration, extraoral prostheses significantly influence psychological well-being, social reintegration, and overall quality of life. Silicone elastomers remain the material of choice for extraoral prostheses because of their flexibility, biocompatibility, chemical inertness, and ability to simulate the texture and translucency of human skin[1,2]. Despite these advantages, long-term esthetic durability—particularly color stability—continues to represent a major clinical limitation.

Clinical observations consistently report that maxillofacial silicone prostheses often require replacement within 6–12 months, primarily due to unacceptable discoloration rather than mechanical failure[3,4]. Color instability is multifactorial and results from intrinsic material degradation and extrinsic environmental exposure. Ultraviolet (UV) radiation is widely recognized as the principal factor responsible for polymer breakdown. Photodegradation induces chain scission, oxidation, and surface roughening, leading to altered light absorption and scattering characteristics that manifest as measurable color change[5,6]. Lemon et al. first demonstrated that artificial weathering produced significant chromatic alteration in facial elastomers and established accelerated aging as a reproducible method for comparative color evaluation[7]. Subsequent investigations confirmed that prolonged UV exposure significantly increases ΔE values in silicone-based materials[8,9].

Accelerated artificial aging protocols—commonly based on ASTM G154 cycles—have therefore become standard for in-vitro evaluation of color stability. However, differences between artificial aging and natural outdoor weathering have been reported, emphasizing the need for standardized methodology when comparing materials[10,11]. In addition to UV exposure, perspiration, environmental pollutants, cosmetic products, disinfectants, and staining agents such as beverages contribute to cumulative discoloration[12-14].

The intrinsic composition of silicone elastomers significantly influences optical stability. Variations in cross-link density, filler type, and pigment system may produce distinct aging responses even among commercially available materials[15,16]. Pigments and opacifiers, while essential for shade matching, may either enhance or compromise color stability depending on their chemical composition and interaction with the silicone matrix[17]. Mancuso et al. reported that cosmetic powders exhibited greater chromatic alteration than ceramic pigments after accelerated aging[8], while Pesqueira et al. demonstrated that pigment–opacifier interactions substantially affect ΔE outcomes[17].

In recent years, nanotechnology has been explored as a strategy to mitigate photodegradation in silicone elastomers. Metal oxide nanoparticles such as titanium dioxide (TiO_2), zirconium dioxide (ZrO_2), cerium oxide (CeO_2), and zinc oxide (ZnO) possess high refractive indices and strong UV-absorbing properties, enabling them to act as photoprotective fillers[18]. Han et al. demonstrated that nano-TiO_2 and nano-CeO_2 significantly reduced color change in pigmented silicone elastomers subjected to artificial aging[19]. Similarly, Bishal et al. reported that titanium dioxide nanocoating maintained ΔE values within clinically acceptable limits after accelerated aging[20]. More recent investigations have reinforced the beneficial role of nano-oxides in enhancing color stability, although concentration, particle size, and dispersion method critically influence performance[21-23].

Zirconium dioxide nanoparticles have attracted increasing attention due to their chemical stability, biocompatibility, and potential mechanical reinforcement properties. Abdalqadir et al. demonstrated a concentration-dependent reduction in color alteration in heat-polymerized silicone elastomers reinforced with ZrO_2 nanoparticles[24]. Zarrati et al. further emphasized that nanoparticle efficacy is closely linked to pigment compatibility and dispersion quality[21]. Recent systematic reviews conclude that although nano-oxide incorporation generally improves optical

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stability, heterogeneity in methodology limits direct comparison across studies[18,25].

Despite growing evidence supporting nanoparticle reinforcement, several gaps remain. Most studies evaluate either a single silicone formulation or a single nanoparticle type, with limited head-to-head comparisons of different heat-polymerized (HTV) silicone systems under standardized aging conditions. Furthermore, while titanium dioxide has been extensively investigated, fewer studies have directly compared TiO_2 and ZrO_2 nanoparticles within identical experimental designs. Given the widespread clinical use of HTV silicones for extraoral prostheses due to their superior mechanical properties[2], direct comparative evaluation of commercially available formulations remains clinically relevant.

Therefore, the present study aims to compare and evaluate the color stability of two heat-polymerized maxillofacial silicone elastomers, intrinsically stained and subjected to artificial aging, with the incorporation of zirconium dioxide and titanium dioxide nanoparticles. By employing standardized specimen preparation, controlled nanoparticle dispersion, ASTM-based accelerated aging, and spectrophotometric ΔE analysis, this investigation seeks to provide clinically meaningful evidence regarding the efficacy of nanoparticle reinforcement in enhancing long-term esthetic stability of maxillofacial prostheses.

➢ *Aim of the Study*

To compare and evaluate the color stability of artificially aged two different types heat polymerized maxillofacial silicone elastomer by addition of zirconium dioxide and titanium dioxide nano particles.

➢ *Objective of the Study*

- To assess and compare the color stability of two different types of heat polymerized maxillofacial silicone elastomers.
- To assess and compare the color stability of two different types of heat polymerized maxillofacial silicone elastomers by addition of zirconium dioxide nano particles.
- To assess and compare the color stability of two different types of heat polymerized maxillofacial silicone elastomers by addition of titanium dioxide nano particles.

II. MATERIALS AND METHODS

➢ *Study Sample and Sample Size*

A total of 120 silicone specimens were fabricated in the form of discs.

➢ *Dimensions of each specimen:*

- Diameter: 20 mm
- Thickness: 3 mm

- *Sample Distribution:*

The specimens were divided into six groups, with 20 samples in each group (n = 20). {Table no 1}

➢ *Materials Used*

- *Heat-Polymerized Maxillofacial Silicone Elastomer*

✓ Technovent Ltd
✓ MP Sai Enterprises

- *Intrinsic Stains (Pigments)*

✓ Compatible with respective silicone systems

- *Nanoparticles*

✓ Zirconium dioxide (ZrO_2) nanoparticles (Nanowings)
✓ Titanium dioxide (TiO_2) nanoparticles (Nanowings)

- *Equipment*

✓ Digital electronic weighing balance
✓ Vacuum mixer
✓ Hydraulic press
✓ Hot air oven
✓ Digital colorimeter
✓ Artificial aging chamber (UV weathering unit)

➢ *Specimen Preparation*

Metal molds were fabricated using laser-cut cast iron sheets with standardized circular cavities (20 mm × 3 mm). Stainless steel plates were used to sandwich the mold to ensure uniform thickness and withstand clamping forces.{Figure 1}

➢ *Preparation of Control Specimens*

For Groups 1 and 2:

- Silicone base (Part A) and catalyst (Part B) were mixed in a 10:1 ratio as per manufacturer's instructions.
- Intrinsic pigment was weighed and mixed with Part A using a digital balance.
- The mixture was homogenized in a vacuum mixer (10 minutes, 360 rpm, −0.09 MPa) to eliminate air incorporation.
- Part B was added and mixed further for 5 minutes.

➢ *Preparation of Experimental Specimens*

For Groups 3–6:

- Pre-weighed nanoparticles (ZrO_2 or TiO_2) were incorporated into silicone Part A along with intrinsic pigments.
- The mixture was homogenized in a vacuum mixer for 10 minutes to ensure uniform nanoparticle dispersion.
- Part B was then added and mixed for an additional 5 minutes.

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➢ *Molding and Polymerization*

- The mixed material was poured into molds using a metal spatula.
- The molds were sealed and subjected to a hydraulic press (0.03 MPa for 5 minutes).

➢ *Finishing and Storage*

- After polymerization, specimens were removed, washed with soap and water, and dried.
- Excess material was trimmed using scissors.
- All specimens were stored in a light-proof black box to prevent premature color changes before testing.

➢ *Artificial Aging Procedure*

Artificial aging was performed using a UV aging chamber in accordance with ASTM G154 Cycle 1.

- *Aging Parameters:*

✓ Wavelength: ~340 nm
✓ Irradiance: 0.89 W/m²/nm
✓ Cycle:

- 8 hours UV exposure at 60 ± 3°C
- 4 hours condensation at 50 ± 3°C

- *Time Intervals:*

Specimens were evaluated at:

✓ Baseline (0 hours)
✓ 252 hours
✓ 504 hours
✓ 1008 hours

➢ *Color Measurement*

Color evaluation was performed using a digital colorimeter/spectrophotometer.

- *Measurement System:*

✓ Based on CIELAB color space

- *Parameters Recorded:*

✓ L* (lightness)
✓ a* (red-green axis)
✓ b* (yellow-blue axis)

- *Calculation of Color Difference:*

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

Where:

✓ ΔL*, Δa*, Δb* represent the difference between baseline and aged values

➢ *Data Collection*

- Color values were recorded at each interval
- ΔE values were calculated for each specimen
- Mean and standard deviation were computed for each group

➢ *Statistical Analysis*

- Data analysis was performed using statistical software (SPSS)
- Descriptive statistics: Mean ± SD
- Inferential statistics:

✓ One-way ANOVA for intergroup comparison
✓ Repeated measures ANOVA for time-based comparison
✓ Post hoc Tukey test for pairwise analysis

- *Level of Significance:*

✓ $p < 0.05$ considered statistically significant

III. RESULTS

Statistical analysis of the collected data was carried out using IBM SPSS Statistics software. The data were initially summarized using descriptive statistics and expressed as mean ± standard deviation (SD) to represent the central tendency and dispersion of the measured values. For inferential statistical analysis, one-way analysis of variance (ANOVA) was applied to compare the mean values among the different study groups. To assess changes in the measured parameters over different time intervals within the same group, repeated measures ANOVA was employed. Furthermore, when significant differences were observed, Tukey's post hoc test was performed for pairwise comparisons to identify the specific groups between which statistically significant differences existed.

The highest color change was observed in Group 2 (MP Sai control control) with a mean ΔE of 3.78 ± 0.10, followed by Group 1 (Technnovent control) with a mean ΔE of 3.30 ± 0.08. This indicates that both control groups exhibited clinically noticeable discoloration after artificial aging.

The incorporation of nanoparticles significantly reduced color change. Among the ZrO_2 groups, Group 4 (MP Sai + ZrO_2) showed a mean ΔE of 2.32 ± 0.07, whereas Group 3 (Technovent+ ZrO_2) demonstrated a lower mean ΔE of 1.82 ± 0.06, indicating improved color stability with the maxillofacial silicone of Technovent Ltd..

Further improvement was observed in TiO_2 reinforced groups. Group 6 (MP Sai + TiO_2) showed a mean ΔE of 1.72 ± 0.06, while Group 5 (Technovent + TiO_2) exhibited the lowest color change with a mean ΔE of 1.32 ± 0.05.

Statistical analysis using one-way ANOVA revealed a highly significant difference between groups ($p < 0.001$). Post hoc Tukey analysis demonstrated that all nanoparticle groups

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differed significantly from control groups, with TiO_2 groups showing superior performance compared to ZrO_2 groups.

➢ *Comparative Color Stability at Different Aging Intervals*

A comparative evaluation of color stability across all six groups at baseline, 252 hours, 504 hours, and 1008 hours demonstrated a progressive increase in color change with increasing aging duration in all groups.

At baseline (0 hours), all groups exhibited comparable initial color coordinates, indicating standardization of specimen fabrication and intrinsic pigmentation prior to aging. No clinically significant differences in color were observed among the groups at this stage.

At 252 hours of artificial aging, the control groups began to show more pronounced color alteration compared to nanoparticle-reinforced groups. Group 5 (Technovent + TiO_2) demonstrated the highest color stability (least color change), followed closely by Group 6 (MP Sai + TiO_2). Group 2 (MP Sai control) showed the least color stability (maximum early color change).

At 504 hours, the same trend continued, with progressive deterioration observed in all groups. The TiO_2 reinforced groups maintained superior resistance to discoloration, particularly Group 5, which remained the most color stable. Among the control groups, Group 2 continued to exhibit the greatest color degradation, followed by Group 1.

At 1008 hours, representing the final artificial aging interval, the cumulative color change was highest in the control groups and lowest in nanoparticle-reinforced groups. Based on final ΔE values, the order of color stability from best to worst was:

Group 5 (Technovent + TiO_2) > Group 6 (MP Sai + TiO_2) > Group 3 (Technovent + ZrO_2) > Group 4 (MP Sai + ZrO_2) > Group 1 (Technovent Control) > Group 2 (MP Sai Control)

Thus, Group 5 consistently demonstrated the greatest resistance to color change throughout the aging process, whereas Group 2 exhibited the poorest color stability at all post-aging intervals.

These findings clearly indicate that nanoparticle incorporation significantly enhanced resistance to artificial aging-induced discoloration, with titanium dioxide proving more effective than zirconium dioxide, and Technovent performing better than MP Sai silicone.

Overall, the results indicate that:

- Nanoparticle incorporation significantly enhances color stability
- Titanium dioxide is more effective than zirconium dioxide
- Technovent maxillofacial silicone exhibits better resistance to discoloration than MP Sai silicone

Group 5 (Technovent + TiO_2) showed the best overall performance

IV. DISCUSSION

Despite significant advancements in material science, color instability of maxillofacial silicone elastomers remains one of the most critical clinical challenges.

One of the primary reasons for prosthesis replacement is not mechanical failure, but progressive discoloration, which compromises esthetics and patient satisfaction. Studies have consistently shown that conventional silicone materials undergo significant color degradation within 6–12 months of clinical use, primarily due to ultraviolet radiation, environmental exposure, and intrinsic material degradation[3,6,8]. This frequent replacement leads to increased financial burden, treatment time, and psychological distress for patients.

Although several strategies have been explored to improve color stability—including intrinsic pigmentation, opacifiers, and surface coatings—none have been completely successful in preventing long-term discoloration. In recent years, nanoparticle incorporation has emerged as a promising approach due to its ability to enhance ultraviolet resistance and reduce polymer degradation. However, the existing literature presents several limitations:

- Most studies evaluate single materials or single nanoparticles, limiting comparative understanding
- There is lack of direct comparison between commonly used nanoparticles, such as zirconium dioxide (ZrO_2) and titanium dioxide (TiO_2)
- Limited data exist on heat-polymerized silicone elastomers, which are widely used clinically
- Variability in aging protocols and methodologies makes it difficult to draw definitive conclusions
- Few studies compare different commercial silicone systems under identical conditions

Furthermore, while titanium dioxide has been extensively studied, evidence comparing its effectiveness with zirconium dioxide within the same experimental design remains insufficient. Similarly, the influence of base material composition on nanoparticle performance has not been adequately explored.

Therefore, there was a clear need for a standardized, comparative in-vitro study that:

- Evaluates the effect of both TiO_2 and ZrO_2 nanoparticles
- Compares two commercially available heat-polymerized silicone elastomers
- Uses uniform specimen preparation and artificial aging protocols
- Provides quantitative color stability analysis using the CIELAB system

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The present study was undertaken to address these gaps and to generate clinically relevant evidence regarding the effectiveness of nanoparticle incorporation in improving the color stability of maxillofacial silicone elastomers.

The present in-vitro study was conducted to evaluate and compare the color stability of two heat-polymerized maxillofacial silicone elastomers with and without the incorporation of zirconium dioxide (ZrO_2) and titanium dioxide (TiO_2) nanoparticles following artificial aging. Color changes were assessed using the CIELAB system and expressed as ΔE values. The results demonstrated that nanoparticle incorporation significantly improved color stability, with TiO_2 showing superior performance compared to ZrO_2, and Technovent Silicone exhibiting better stability than MP Sai material.

Maxillofacial silicone elastomers are inherently susceptible to discoloration due to environmental and material-related factors. Early foundational work by Polyzois et al.[2] and Lemon et al.[5] established that ultraviolet (UV) radiation is the primary cause of color degradation through polymer chain scission and pigment oxidation. These processes lead to alterations in light reflection and absorption, ultimately resulting in perceptible color change.

Further studies have demonstrated that aging is a multifactorial phenomenon involving thermal cycling, humidity, oxygen exposure, and biological factors such as sebum and perspiration[8,14]. Hatamleh and Watts[3] reported that combined environmental exposure produces greater degradation than UV radiation alone, suggesting that clinical conditions are more complex than laboratory simulations.

The findings of the present study are consistent with these observations, as the control groups exhibited the highest ΔE values, confirming the inherent instability of unmodified silicone elastomers.

Accelerated artificial aging is widely used to simulate long-term clinical service conditions. In the present study, ASTM G154 cycles were employed, which include alternating UV exposure and condensation phases. This methodology has been validated by several investigators as a reliable predictor of clinical aging[6,10].

The significant increase in ΔE values observed in control groups aligns with previous reports by dos Santos et al.[6] and Goiato et al.[4], who demonstrated progressive discoloration with increasing aging duration. Nair et al.[10] further confirmed that artificial aging produces greater color change compared to natural weathering, although the pattern of degradation remains consistent.

Recent systematic reviews have highlighted the lack of standardization in aging protocols as a limitation in comparative research[18,25]. Nevertheless, accelerated aging remains an essential tool for evaluating material performance under controlled conditions.

➢ *Effect of Nanoparticle Incorporation*

- *Zirconium Dioxide (ZrO_2)*

The incorporation of ZrO_2 nanoparticles in the present study resulted in a significant reduction in ΔE values compared to control groups. This improvement can be attributed to the high refractive index and UV-blocking capability of zirconium dioxide, which reduces photon penetration and minimizes polymer degradation.

These findings are consistent with Abdalqadir et al.[24], who reported a concentration-dependent reduction in color change following ZrO_2 incorporation. Similarly, Zarrati et al.[21] demonstrated that nano-oxide additives significantly improve color stability, although their effectiveness depends on pigment compatibility and dispersion.

However, ZrO_2 groups in the present study showed slightly higher ΔE values than TiO_2 groups, indicating comparatively lower efficiency in preventing photodegradation.

- *Titanium Dioxide (TiO_2)*

TiO_2 nanoparticles exhibited the greatest improvement in color stability, with ΔE values falling within clinically acceptable limits. This can be explained by the superior UV absorption capacity and photocatalytic stability of titanium dioxide.

Han et al.[7,19] demonstrated that nano-TiO_2 acts as an effective opacifier and UV stabilizer, significantly reducing discoloration in silicone elastomers. Bishal et al.[30] further confirmed that TiO_2 nanocoating enhances resistance to UV-induced degradation.

Systematic evidence by Sonnahalli and Chowdhary[18] supports these findings, indicating that TiO_2 is one of the most effective nanoparticle additives for improving color stability. The results of the present study strongly corroborate this conclusion.

➢ *Influence of Base Material Composition*

An important observation in the present study was the superior performance of Technovent silicone compared to MP Sai across all groups. This suggests that intrinsic material properties play a critical role in color stability.

Previous studies have demonstrated that differences in polymer structure, cross-link density, filler composition, and pigment systems significantly influence aging behavior[12,15,16]. Goiato et al.[15] reported that even commercially available silicones exhibit varying degrees of discoloration under identical conditions.

Thus, the improved performance of Technovent silicone may be attributed to its inherent formulation, which may offer better resistance to oxidative and photochemical degradation.

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The interpretation of color difference (ΔE) values is of paramount importance in assessing the clinical acceptability of maxillofacial prosthetic materials. In the present study, color changes were evaluated using the CIELAB system, which remains the gold standard for objective color assessment in dental and maxillofacial research. Based on established perceptibility and acceptability thresholds, ΔE values were categorized as follows:

- ΔE > 3.3 → Clinically unacceptable discoloration
- ΔE 2–3 → Perceptible but clinically acceptable
- ΔE < 2 → Clinically imperceptible

These thresholds are widely supported in prosthodontic literature and reflect the limits of human visual perception under clinical conditions.

In the present study, the control groups (without nanoparticle incorporation) consistently demonstrated ΔE values exceeding 3.3, indicating clinically unacceptable discoloration. This finding corroborates earlier studies which have shown that conventional silicone elastomers undergo significant chromatic alteration following exposure to ultraviolet radiation and environmental aging[3,6,8]. Such discoloration often necessitates early replacement of prostheses, contributing to increased financial burden and psychological distress for patients.

In contrast, the incorporation of nanoparticles—particularly titanium dioxide (TiO_2)—resulted in ΔE values within clinically acceptable or even imperceptible limits. This suggests that nanoparticle reinforcement effectively mitigates the extent of color degradation, thereby enhancing the esthetic longevity of maxillofacial prostheses. From a clinical perspective, maintaining ΔE values below the perceptibility threshold is crucial, especially in highly visible facial regions where even minor color discrepancies can compromise patient satisfaction.

Furthermore, it is important to recognize that clinical perception of color change is influenced by multiple factors, including lighting conditions, observer variability, surrounding tissues, and prosthesis location. Therefore, achieving ΔE values within imperceptible limits represents a significant advancement toward improving clinical outcomes.

While the present study was conducted under controlled experimental conditions and demonstrated clear trends, certain limitations must be acknowledged.

Firstly, the in-vitro nature of the study restricts direct extrapolation of results to clinical scenarios. In the oral and facial environment, prosthetic materials are subjected to a complex combination of biological, mechanical, and environmental factors that are difficult to replicate in laboratory settings. Factors such as patient-specific habits, hygiene practices, and environmental exposure may significantly influence long-term performance.

Secondly, the study did not incorporate biological aging factors, such as perspiration, sebum, microbial colonization, and cosmetic application. Previous investigations have demonstrated that such factors can accelerate degradation by altering surface chemistry and increasing susceptibility to staining and oxidation[8,14]. The absence of these variables may result in an underestimation of actual clinical discoloration.

Another limitation is the use of a single nanoparticle concentration. Although the selected concentration was based on existing literature, it is well established that nanoparticle effectiveness is concentration-dependent. Both insufficient and excessive nanoparticle loading can adversely affect optical and mechanical properties. Therefore, evaluation of multiple concentrations would provide a more comprehensive understanding of optimal formulations.

Additionally, the present study did not assess long-term clinical performance or durability under real-life conditions. While artificial aging provides valuable insights, it cannot fully replicate prolonged exposure over months or years. Clinical trials are essential to validate the in-vitro findings.

Uniform dispersion of nanoparticles is critical for achieving optimal UV shielding and preventing agglomeration, which can negatively impact both esthetics and material properties. Variability in dispersion techniques across studies remains a significant limitation in current research, as highlighted in recent systematic reviews[25].

The results of the present study open several avenues for future research and development in the field of maxillofacial prosthetic materials.

One of the most important areas is the optimization of nanoparticle concentration and distribution. Future studies should explore a range of concentrations to determine the ideal balance between color stability, mechanical strength, and translucency. Advanced dispersion techniques, including ultrasonic mixing and surface modification of nanoparticles, may further enhance their effectiveness.

The development of hybrid nanoparticle systems represents another promising direction. Combining different nanoparticles, such as TiO_2 with SiO_2 or ZnO, may produce synergistic effects by improving UV absorption, mechanical properties, and resistance to environmental degradation. Recent studies have demonstrated that hybrid nanofillers can significantly enhance optical stability compared to single nanoparticle systems[39,36,34].

There is also growing interest in the integration of digital technologies and additive manufacturing in maxillofacial prosthetics. The incorporation of nanoparticles into 3D-printable silicone materials could revolutionize prosthesis fabrication by enabling precise control over material properties and color matching. Digital workflows, including CAD/CAM and colorimetric mapping, may further improve accuracy and reproducibility.

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Long-term clinical trials are essential to validate in-vitro findings and establish evidence-based guidelines for material selection. Such studies should consider patient-related factors, environmental exposure, and maintenance protocols to provide a comprehensive evaluation of prosthetic performance.

Another important direction is the development of smart or responsive materials, such as UV-resistant coatings, self-cleaning surfaces, or pigments with enhanced photostability. These innovations could significantly extend the service life of maxillofacial prostheses.

Finally, there is a critical need for standardization of testing protocols, particularly in artificial aging and color measurement methodologies. Uniform guidelines would facilitate comparison across studies and accelerate the translation of research findings into clinical practice.

The findings of the present study, combined with emerging evidence, suggest that the integration of nanotechnology with advanced material science and digital workflows has the potential to significantly improve the esthetic and functional longevity of maxillofacial prostheses. Continued interdisciplinary research will be essential in achieving this goal and enhancing patient quality of life.

V. CONCLUSION

Maxillofacial prosthetic rehabilitation is an essential component of restoring facial esthetics, function, and psychological well-being in patients with congenital defects, trauma, or acquired maxillofacial deformities following oncologic resection. Among the materials available for fabrication of facial prostheses, silicone elastomers remain the material of choice due to their flexibility, biocompatibility, life-like appearance, and ability to simulate skin texture. However, one of the most significant limitations associated with silicone prostheses is their poor long-term color stability, leading to frequent prosthesis replacement and reduced patient satisfaction.

Color degradation in maxillofacial silicone elastomers occurs due to multiple factors including ultraviolet radiation, thermal cycling, humidity, oxidation, environmental exposure, intrinsic pigment instability, and routine maintenance procedures. To overcome these limitations, nanoparticle reinforcement has emerged as a promising strategy for improving material performance, particularly in terms of ultraviolet resistance and esthetic longevity.

The present in-vitro study was undertaken to compare and evaluate the color stability of intrinsically stained artificially aged two different heat-polymerized maxillofacial silicone elastomers following the incorporation of zirconium dioxide (ZrO_2) and titanium dioxide (TiO_2) nanoparticles.

The findings revealed that control groups demonstrated the highest degree of color change following artificial aging, confirming the inherent susceptibility of conventional silicone elastomers to photodegradation. Nanoparticle incorporation significantly improved color stability in all experimental groups.

Among the nanoparticle-reinforced groups, titanium dioxide demonstrated superior performance compared to zirconium dioxide, indicating greater ultraviolet shielding and protection against oxidative degradation. The Technovent silicone groups consistently showed better color stability compared to MP Sai silicone, suggesting that intrinsic material composition also influences aging resistance.

Statistical analysis demonstrated a highly significant difference among groups ($p < 0.001$), confirming the effectiveness of nanoparticle incorporation in reducing color degradation.

The results indicate that nanoparticle reinforcement significantly enhances the esthetic longevity of maxillofacial silicone elastomers and may reduce the need for frequent prosthesis replacement.

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