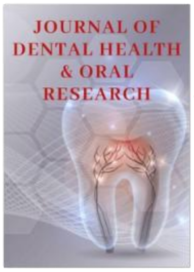

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Hydrothermal Aging of High-Translucency Zirconia: A Narrative Review of Degradation Mechanisms, Clinical Implications and Material Selection Criteria

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Abstract

High-translucency zirconia formulations are increasingly used in restorative dentistry, yet their susceptibility to hydrothermal aging remains a critical clinical concern.
Objective: This narrative review examines how hydrothermal aging influences the degradation behavior, clinical performance and material selection criteria of high-translucency zirconia restorations.
Methods: Peer-reviewed literature was searched through PubMed, ScienceDirect and Scopus, covering crystallographic mechanisms, accelerated aging protocols, *In-vivo* evidence, clinical failure modes, processing variables and selection frameworks.
Results: Hydrothermal aging drives a tetragonal-to-monoclinic phase transformation that progressively reduces flexural strength, translucency and surface integrity, with 4Y-TZP and 5Y-TZP materials showing greater susceptibility than conventional 3Y-TZP. *In-vivo* degradation is substantially faster than laboratory models predict. Patient risk factors and processing variables further modulate clinical outcomes.
Conclusion: Material selection must be individualized using a risk-stratified approach. Standardized protocols and long-term clinical trials remain priorities for future research.

Keywords: Hydrothermal Aging; Low-Temperature Degradation; High-Translucency Zirconia; 4Y-TZP; 5Y-TZP; Phase Transformation; Material Selection; Restorative Dentistry

Introduction: Zirconia in Contemporary Restorative Dentistry; Evolution, Promise and the Aging Problem

Zirconia was initially introduced into restorative dentistry as a high-strength ceramic material intended primarily for posterior restorations and framework-supported prostheses. Conventional 3Y-TZP zirconia became widely adopted because of its excellent fracture resistance, flexural strength, chemical stability and biocompatibility; however, its relatively opaque appearance limited its esthetic potential [1]. As clinical demand for more natural-looking restorations increased, manufacturers began developing zirconia materials with enhanced optical properties while attempting to preserve acceptable mechanical performance [2].

Contemporary zirconia materials are classified according to yttria content and translucency, including conventional 3Y-TZP, partially stabilized 4Y-TZP, highly translucent 5Y-TZP and multilayer zirconia systems. Increasing yttria concentration enhances translucency by raising the cubic phase content of the material, allowing restorations to better reproduce the appearance of natural dentition [2]. CAD/CAM technologies have further expanded clinical applications by enabling more precise control over restoration geometry and optical gradient [3].

The adoption of zirconia in modern prosthodontics is driven by its exceptional flexural strength, fracture toughness and wear resistance, which contribute to restoration longevity. The material also demonstrates excellent biocompatibility with minimal inflammatory response, making it a reliable long-term option for intraoral use [1]. Advancements in high-translucency formulations have improved light transmission properties and the development of monolithic zirconia restorations has reduced complications associated with veneering porcelain, improving overall clinical reliability [3].

Despite these advantages, concerns regarding the long-term stability of zirconia materials under oral environmental conditions have become increasingly relevant. One of the principal concerns is Low-Temperature Degradation (LTD), also referred to as hydrothermal aging, which occurs when zirconia is exposed to humid environments over time, leading to progressive structural degradation that may compromise the material's long-term clinical performance [4].

Hydrothermal aging has been associated with reductions in translucency, color stability and flexural strength, all of which may affect the durability and reliability of zirconia restorations. Because high-translucency zirconia is increasingly used in esthetically demanding situations, understanding the effects of aging has become especially important. Current literature therefore emphasizes the need to evaluate the long-term stability of these materials under simulated oral conditions to better predict their clinical behavior and longevity [5].

This narrative review examines current evidence regarding hydrothermal aging and its implications for restorative dentistry. The central question is: How does hydrothermal aging influence the degradation behavior, clinical implications and material selection considerations of high-translucency zirconia? The review is organized across sections addressing the crystallographic basis of LTD, *in-vitro* and *in-vivo* evidence, clinical failure modes and patient risk factors, processing variables, material selection criteria and a synthesizing conclusion.

Crystallographic Basis of Low-Temperature Degradation: Phase Transformation and Structural Consequences

Achieving increased translucency in zirconia requires modifying the internal stabilizing agents, a change that carries important structural consequences. One of the most significant challenges in both research and clinical practice is understanding low-temperature degradation, which occurs when zirconia contacts moisture over time [5]. This hydrothermal aging process attacks the same crystalline architecture that provides the ceramic with its mechanical durability and understanding this mechanism at the microstructural level is fundamental to predicting long-term clinical behavior [6].

At the core of this degradation lies the spontaneous transformation of the zirconia crystal lattice from the tetragonal phase to the monoclinic phase. Pure zirconia at room temperature is monoclinic; dental applications require it to be retained in the tetragonal form through stabilization with Yttria (Y_2O_3) [6]. When external moisture disrupts this metastable equilibrium, the grains begin to expand as they shift into the larger monoclinic arrangement. This phase transformation is martensitic in nature, meaning it proceeds through a coordinated atomic movement rather than through diffusion. As the crystal volume increases by approximately 3 to 4%, internal stresses accumulate rapidly within the dense ceramic matrix. While this expansion can initially provide a toughening effect by arresting small cracks, it becomes a destructive force under sustained hydrothermal conditions [7].

Water is the primary environmental trigger for these crystallographic changes in the oral environment. Hydroxyl ions interact with oxygen vacancies that arise from the yttria stabilization process, progressively destabilizing the dopant in regions surrounding individual zirconia grains [7]. As yttria is depleted from grain boundary areas, resistance to phase transformation is lost. In high-translucency formulations such as 4Y-TZP and 5Y-TZP, this vulnerability is amplified because these compositions contain a higher proportion of the cubic phase and larger grain sizes, both of which reduce transformation resistance. The result is that the material surface becomes a site of structural instability that propagates toward the restoration bulk [8].

The structural consequences manifest initially as microscopic cracks that propagate through the surface layer. These microcracks provide new pathways for water penetration, creating a self-sustaining autocatalytic cycle [8]. As more grains transform, the restoration surface loses its original smoothness, increasing roughness and creating conditions that promote abrasion of opposing dentition. The progressive loss of grain cohesion can ultimately result in grain pullout, where entire crystal segments detach from the ceramic body. These cumulative structural defects substantially reduce the flexural strength and fracture toughness for which zirconia is valued clinically [9].

Susceptibility to LTD differs meaningfully across zirconia compositions. Conventional 3Y-TZP demonstrates the greatest resistance to hydrothermal aging because of its higher tetragonal phase content and smaller grain size. Fourth- and fifth-generation formulations (4Y-TZP and 5Y-TZP), which contain progressively more cubic phase to enhance translucency, exhibit reduced transformation resistance and are therefore more vulnerable to LTD under the same environmental conditions [9]. These compositional differences are characterized through X-ray diffraction analysis, which quantifies monoclinic phase content; scanning electron microscopy, which documents surface microcracking and grain pullout; and profilometry, which measures changes in surface roughness as degradation progresses [10].

In-vitro and *In-vivo* Evidence: What Aging Studies Tell Us About Clinical Performance

High-translucency zirconia has been progressively incorporated into modern restorative dentistry because of its superior esthetic profile and generally acceptable mechanical behavior. However, the long-term predictability of these materials under hydrothermal aging conditions remains a clinically important concern, particularly as newer generations are designed to achieve translucency through modifications of microstructure and yttria content.

Hydrothermal aging is primarily evaluated through accelerated laboratory protocols intended to reproduce long-term oral exposure within condensed timeframes. The most widely used methods include autoclave aging under ISO 13356 conditions (134°C, 0.2 MPa), thermocycling and prolonged immersion in humid environments at elevated temperatures [9]. These protocols allow standardized comparison among materials and provide insight into their susceptibility to degradation over time. However, their capacity to predict true clinical behavior remains limited. Unlike laboratory conditions, the oral environment involves cyclic occlusal loading, saliva, biofilm accumulation, pH fluctuations, thermal variation and parafunctional activity; all of which interact in ways that accelerated protocols cannot fully replicate [10]. Accelerated aging studies are therefore useful for identifying degradation trends but should not be interpreted as direct predictors of intraoral performance [11].

In-vitro research consistently demonstrates that hydrothermal aging can alter flexural strength, fracture toughness, surface roughness, translucency and monoclinic phase content, though the magnitude of these effects varies considerably across zirconia generations and experimental methodologies. Studies evaluating the mechanical and optical properties of zirconia ceramics have shown that highly translucent materials exhibit distinct degradation patterns compared to conventional systems, with reductions in flexural strength reported across multiple formulations following accelerated aging [11]. Research specifically focused on optical outcomes has confirmed that aging reduces the translucency parameter in several monolithic zirconia formulations, a finding of particular clinical relevance given that these materials are frequently selected for esthetically demanding anterior restorations [12].

Comparative evidence across zirconia generations highlights a fundamental trade-off between aesthetics and mechanical reliability. Conventional 3Y-TZP generally demonstrates greater resistance to degradation and superior fracture behavior; meanwhile, 4Y-TZP and 5Y-TZP formulations achieve improved translucency at the cost of reduced mechanical stability under aging conditions [8]. This distinction is especially relevant in posterior restorations, where functional loading amplifies the clinical consequences of surface degradation and diminished fracture resistance. Although clinical evidence is more limited than laboratory data, available longitudinal studies generally report acceptable survival rates for monolithic zirconia restorations. Nevertheless, complications including chipping, marginal deterioration, increased surface roughness and fracture continue to be reported, particularly in restorations subjected to high occlusal stress. Importantly, *In-vivo* research has demonstrated that aging in the oral environment may progress approximately three times faster than conventional laboratory extrapolations predict [13]. This discrepancy suggests that current accelerated aging models substantially underestimate the complexity and pace of intraoral degradation, which has direct implications for how *In-vitro* findings should be applied clinically.

A major gap in the current literature is the absence of standardized aging protocols and well-designed longitudinal clinical studies capable of correlating laboratory findings with real restorative outcomes [13]. The variability in aging conditions, specimen geometry, material composition and outcome measures across published studies makes direct comparison difficult and limits the strength of conclusions that can be drawn. The systematic review by Hajhamid, et al., confirmed that while accelerated aging significantly affects the crystalline structure and optical properties of monolithic zirconia, the heterogeneity of published evidence makes definitive generalizations across zirconia generations problematic [14].

In summary, the available evidence supports the general clinical reliability of high-translucency zirconia but also establishes that aging behavior is highly material-dependent. Findings cannot be generalized across generations and the pace of *In-vivo* degradation likely exceeds what laboratory models suggest. These limitations underpin the clinical failure analysis developed in the following section.

Clinical Implications of Hydrothermal Aging: Restorative Outcomes, Failure Modes and Patient Risk Factors

Hydrothermal aging is not merely a laboratory phenomenon; it is a clinically meaningful process that directly affects the function, esthetics and long-term survival of zirconia restorations. The structural changes described in preceding sections translate into specific failure modes and patient-level consequences that clinicians must recognize and anticipate during treatment planning [8].

The most serious clinical consequence of LTD-driven degradation is catastrophic fracture, which is particularly prevalent in posterior restorations subjected to sustained high occlusal forces. Restorations with insufficient occlusal thickness are especially vulnerable, as reduced material volume limits the capacity to redistribute load and resist crack propagation. Flinn, et al., demonstrated that hydrothermal aging produced a statistically significant decrease in the flexural strength of yttria-stabilized tetragonal zirconia, attributing this reduction to the tetragonal-to-monoclinic phase transformation that accumulates microcracks over time [15]. Beyond catastrophic fracture, surface-level failure modes include loss of surface polish, increased roughness and clinically perceptible color shifts, all of which compromise the esthetic stability of restorations in anterior regions. Marginal deterioration, expressed as microchipping or gap formation at restoration margins, can also compromise cement seal integrity and long-term retention [16].

Patient-related factors significantly modulate the rate and severity of hydrothermal degradation in clinical settings. Bruxism and parafunctional habits impose cyclic mechanical stress that compounds the microstructural weakening induced by LTD, accelerating crack propagation and increasing fracture likelihood [2]. Clinical studies have demonstrated that a substantial proportion of catastrophic failures in monolithic zirconia restorations occur in patients with confirmed bruxism, reinforcing the importance of parafunction screening before material selection [16].

An acidic oral environment, whether from dietary habits, Gastroesophageal Reflux Disease (GERD) or frequent acidic beverage consumption, alters the chemical equilibrium at the zirconia surface in ways that may potentiate the hydroxyl-driven destabilization of yttria [7]. Xerostomia reduces salivary buffering and lubrication, increasing abrasive wear and potentially altering the ionic composition of the oral fluid in contact with the restoration [5].

The location and design of the restoration introduce additional clinical variables. Anterior restorations experience lower functional loads but demand high optical stability and color consistency, making them particularly sensitive to the translucency and color shifts associated with LTD [13]. Posterior restorations, by contrast, are subject to masticatory forces that can exceed 500 N in some patients, placing greater demands on the residual mechanical properties of an aged material. Restorations in bridge configurations concentrate stress at connector regions and present higher risk of fracture when the material's mechanical properties are compromised by aging. In patients with limited occlusal space or aggressive preparation designs, the restoration may already operate near its mechanical threshold, leaving little margin for the strength reductions that LTD produces over time [17]. High-risk patient profiles warrant particularly careful material selection and follow-up planning. Patients with severe bruxism, documented GERD, significant xerostomia or a history of ceramic fracture represent a subgroup in whom the long-term reliability of highly translucent zirconia formulations may be substantially reduced [1]. For these patients, the clinical strategy should prioritize mechanical performance over esthetic optimization, accepting a degree of compromise in translucency in exchange for greater resistance to hydrothermal degradation.

Surface Treatments, Sintering Protocols and Processing Variables: Their Role in Aging Susceptibility

The clinical behavior of a zirconia restoration is shaped not only by its composition but also by every fabrication decision made before it reaches the patient's mouth. Sintering protocol, milling strategy, surface treatment and cementation technique each influence the microstructural integrity of the final restoration and, consequently, its susceptibility to hydrothermal aging [17].

Zirconia dental crowns are fabricated using one of two primary approaches: soft-state milling of pre-sintered blocks followed by final sintering or hard milling of fully sintered material. Soft-state milling is more common clinically because it reduces machining time, decreases bur wear and introduces fewer surface defects; however, it requires fabricating the restoration approximately 20 to 30% oversized to compensate for sintering shrinkage [3]. Hard milling eliminates shrinkage compensation but subjects the ceramic to greater mechanical stress during cutting and the associated friction and heat generation can induce surface microcracking or localized phase transformation that may serve as initiation sites for LTD [18]. In both approaches, sintering temperature and cooling rate are critical determinants of grain size distribution and residual stress state; faster cooling and optimized sintering programs have been associated with microstructural configurations that reduce LTD susceptibility in translucent zirconia formulations [5].

Surface treatments applied after milling but before or after sintering have a measurable impact on aging resistance. Polishing to a fine surface finish reduces the density of surface flaws and decreases initial roughness, limiting moisture ingress that drives LTD. Conversely, coarse grinding or intraoral adjustment without adequate coolant can introduce subsurface microcracks and surface phase transformation that accelerate degradation [8]. Glazing has been evaluated as a protective measure, with some evidence suggesting it can transiently reduce water penetration; however, the durability of the glaze layer under occlusal loading and its long-term contribution to LTD resistance remain under investigation. Alumina air-abrasion of the intaglio surface, commonly performed to enhance adhesive bonding, creates a controlled increase in surface area without significantly compromising bulk mechanical properties of 3Y-TZP; though in higher-translucency materials, the implications for aging susceptibility may differ and require further study [19].

The effect of hydrothermal aging is also sensitive to the specific testing conditions used in laboratory research. Studies have evaluated multiple aging modalities including autoclave hydrothermal aging, thermocycling, ultraviolet light exposure and xenon light irradiation, finding that each produces distinct patterns of optical and mechanical change [12]. Hydrothermal aging has been associated with translucency changes that are thickness-dependent, with thinner specimens exhibiting more pronounced effects [5].

Cementation strategy is another underappreciated processing variable in the context of LTD susceptibility. Research has demonstrated that both cement type and cementation technique influence fracture load and stress distribution in zirconia crowns. Resin-based cements produce higher fracture loads in 3Y-TZP crowns compared to zinc phosphate cements, likely because adhesive systems improve load distribution across the restoration-tooth interface and partially compensate for surface microdefects [19]. Because zirconia is not susceptible to acid etching in the same manner as silica-based ceramics, surface activation through alumina air-abrasion or the application of phosphate-containing primers is recommended prior to resin cementation. Cement selection should not be regarded as a primary strategy for preventing hydrothermal degradation at the ceramic surface; its role is primarily mechanical, not crystallographic [20].

Intraoral adjustment of zirconia restorations represents a particularly important clinical risk point. Grinding with rotary instruments without adequate water coolant generates sufficient heat to induce surface phase transformation, creating localized monoclinic-phase zones that serve as preferential initiation sites for LTD propagation. When adjustments are unavoidable, fine-grit diamond burs with continuous water irrigation should be used, followed by thorough polishing to remove damaged surface layers [19].

Material Selection Criteria and Clinical Decision-Making: A Risk-Stratified Framework for High-Translucency Zirconia

Material selection for zirconia restorations should not be understood solely as an esthetic decision; it is a risk management exercise grounded in the mechanical, biological and processing evidence reviewed in preceding sections. Translating that evidence into clinical practice requires a structured framework that accounts for functional loading, esthetic requirements, patient risk profile and restoration design [21].

A risk-stratified approach begins by distinguishing low-load esthetic cases from restorations placed in high-demand functional environments. In posterior crowns, cases involving bruxism or parafunctional habits, restorations with limited occlusal clearance and multi-unit fixed partial dentures, conventional 3Y-TZP continues to represent the most mechanically predictable option. Its superior flexural strength, fracture toughness and resistance to hydrothermal aging make it the appropriate default where function takes precedence over esthetic optimization [22,23].

Fifth-generation 5Y-TZP offers superior translucency through its higher cubic phase content, making it optically well-suited for anterior single-unit restorations in patients with low functional risk [24]. However, this esthetic advantage comes at the cost of reduced flexural strength and fracture toughness, which limits its safe application to low-load anterior restorations. It should not be selected for posterior restorations, bruxism patients or bridge frameworks without careful case-by-case evaluation [21,23].

Fourth-generation 4Y-TZP occupies a clinically valuable middle ground, offering a balance between the mechanical resilience of 3Y-TZP and the improved translucency of 5Y-TZP. It represents a reasonable choice for cases with moderate functional and esthetic demands, such as anterior restorations in patients with average occlusal loads or premolar crowns in non-bruxist patients [24]. *In-vitro* evidence confirms that 4Y-TZP materials maintain reasonable stability after thermomechanical aging, though their fracture toughness values remain lower than those of 3Y-TZP [21].

For cases requiring an esthetic transition from incisal translucency to cervical opacity, multilayer zirconia may offer advantages; however, the mechanical limitations of the most translucent incisal layer must still be considered. Multilayer designs do not eliminate the vulnerability of the cubic-rich regions to hydrothermal aging and their selection should follow the same risk-based logic applied to other high-translucency formulations [22,23].

Restoration thickness significantly influences fracture resistance and must be planned in relation to the zirconia generation selected. For monolithic zirconia restorations, minimum occlusal thicknesses in the range of 0.7 to 1.0 mm for 3Y-TZP and 1.0 to 1.5 mm for higher-translucency formulations have been proposed based on available *In-vitro* evidence, though these values continue to be refined as clinical data accumulate. Extremely thin restorations in high-translucency materials exhibit less predictable fracture behavior and should be approached with caution, particularly in posterior regions [22].

Cementation strategy should complement material selection. In minimally invasive preparations or situations where restoration thickness is reduced, adhesive protocols using resin cements may be preferred because they improve stress distribution and support the restoration structurally [25]. In cases where adequate thickness, retention form and higher-strength materials are present, conventional cementation may be sufficient. Cement selection does not modify the zirconia surface's susceptibility to hydrothermal aging and should not be substituted for appropriate material selection [22,25].

Clinical follow-up should be individualized according to the patient's risk profile. Patients with high-translucency zirconia restorations in load-bearing positions, particularly those with parafunctional habits or acidic oral environments, should be evaluated at shorter intervals. Early signs of aging-related deterioration include loss of surface polish, perceptible color shifts, increased surface roughness on probing or minor marginal chipping [26]. Identifying these changes early allows for timely intervention before catastrophic failure occurs [22,23].

In summary, material selection for high-translucency zirconia should be individualized, evidence-based and guided by a realistic appraisal of the functional and biological demands of each clinical case. Future research should prioritize standardized aging protocols, long-term randomized clinical trials and novel zirconia formulations with improved aging resistance that do not sacrifice mechanical reliability for esthetic gain.

Conclusion

This narrative review synthesizes current evidence on the mechanisms, clinical consequences and practical management of hydrothermal aging in high-translucency zirconia. The tetragonal-to-monoclinic phase transformation driven by moisture exposure represents a fundamental structural vulnerability that is amplified in 4Y-TZP and 5Y-TZP formulations relative to conventional 3Y-TZP. *In-vitro* studies consistently demonstrate material-specific degradation patterns affecting flexural strength, translucency and surface integrity; while *In-vivo* data suggest that clinical aging progresses at a rate substantially exceeding laboratory prediction. Patient-related risk factors, including bruxism, gastroesophageal reflux and xerostomia, further accelerate degradation, as do suboptimal processing decisions such as inadequate cooling during intraoral adjustment or inappropriate surface treatment protocols.

A risk-stratified clinical approach, informed by the evidence reviewed across these sections, provides the most rational basis for material selection. Clinicians should match zirconia generation to the functional and esthetic demands of each case rather than defaulting to higher-translucency materials based on esthetic preference alone. Processing discipline, appropriate cementation strategy and structured follow-up complete the clinical framework.

Significant evidence gaps remain. Standardized aging protocols, long-term prospective clinical studies and investigation of novel zirconia formulations capable of combining aging resistance with improved optical properties represent priority areas for future research. Until that evidence is available, clinicians are advised to apply the conservative, patient-centered decision-making framework outlined in this review.

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Ethical Statement
The project did not meet the definition of human subject research under the purview of the IRB according to federal regulations and therefore was exempt.

Informed Consent Statement
Not applicable.

Authors' Contributions
All authors contributed equally to this paper.

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