Research Article

Cleaning-Induced Changes in Directly 3D-Printed and Thermoformed Clear Aligners: Surface Integrity, Optical Stability and Mechanical Properties—A Narrative Review

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Abstract

Background: Clear aligners are manufactured by thermoforming polymer sheets or by direct three-dimensional (3D) printing. Cleaning is necessary for maintaining hygiene and aesthetics, but repeated mechanical or chemical exposure may alter material properties. These effects may differ between aligner systems because manufacturing technology and polymer composition are not interchangeable. Aim: To review evidence on cleaning-induced changes in the surface, optical and mechanical properties of directly 3D-printed and thermoformed clear aligners and discuss their clinical implications. Methods: This narrative review synthesises the supplied studies of in vitro and in vivo cleaning protocols for clear aligners and related thermoplastic orthodontic appliances. Outcomes included surface roughness and morphology, colour stability, translucency, light transmittance, hardness, elastic modulus, tensile strength and biofilm removal. Results: Cleaning-related changes varied by material, product, protocol and measurement method. Brushing, particularly with toothpaste, altered surface roughness in some materials; chemical and ultrasonic methods produced variable surface and optical effects. While some studies revealed no discernible improvements in specific mechanical qualities, others observed enhanced biofilm clearance along with increased roughness. Direct comparisons showed material- and brand-dependent optical and surface differences, but formulation and thickness differences limited attribution to manufacturing method alone. Evidence connecting laboratory changes with clinically meaningful deterioration remains limited. Conclusion: No universally superior cleaning protocol can be established for all aligner systems. Cleaning should balance hygiene efficacy with material preservation and follow material-specific guidance. Standardised comparative studies and longer-term clinical research are needed.

Keywords: Clear aligners; 3D printing; thermoforming; cleaning protocols; surface roughness; colour stability; optical properties; mechanical properties.

1. Introduction

Clear aligner therapy is a well-established orthodontic treatment option, with aesthetics and removability among its practical advantages. Aligners are worn for prolonged periods and are repeatedly removed for eating and oral hygiene. Maintaining cleanliness and appearance is therefore important, but cleaning is also a repeated exposure that may influence the polymer surface and other material properties. Research has assessed colour, translucency, surface characteristics and mechanical behaviour after different cleaning protocols, showing that hygiene efficacy and material preservation should be considered together. [1–5]

Conventionally, aligners are produced by thermoforming a polymer sheet over a 3D printed dental model. Direct three-dimensional (3D) printing offers an alternative in which the appliance is built layer by layer from a digital design using a printable resin system. These are manufacturing approaches, not single material categories: thermoformed products may differ in polymer composition and layer structure, while printed systems use different resin formulations. Consequently, differences observed among commercial products cannot automatically be attributed to manufacturing method alone. [1–3]

Cleaning protocols include brushing, toothpaste-assisted brushing, immersion in chemical cleaning solutions, effervescent tablets and ultrasonic treatment. Their effects depend on the cleaning agent, mechanical action, exposure conditions and material tested. A change in one outcome should not be assumed to indicate a corresponding change in another: colour difference is not equivalent to translucency, surface roughness is not a direct measure of biofilm, and hardness or elastic modulus alone does not establish the force delivery of a complete appliance.

This narrative review examines cleaning-induced changes in surface integrity, optical stability and mechanical properties, with particular attention to evidence directly comparing printed and thermoformed aligners. It also considers biofilm removal and the limitations that prevent laboratory observations from being translated directly into clinical recommendations. The aim is not to nominate one universally superior cleaning method, but to identify material-specific patterns and research priorities.

2. Material characteristics and manufacturing differences

Thermoformed aligners are made by heating a prefabricated polymer sheet and adapting it over a dental model. The studies reviewed include Essix and Scheu foils and multilayer thermoplastic polyurethane (TPU) systems. Although these products share a general manufacturing process, their composition, thickness and construction may differ. Their responses to cleaning should therefore be interpreted at the level of the tested product rather than generalised to every thermoformed aligner. [1, 2]

Directly printed aligners are produced from a digital design through layer-by-layer fabrication. The reviewed studies include printed materials such as Nexdent and Tera Harz TC-85, as well as polyurethane-based printed specimens. These products do not constitute a chemically uniform category. Results obtained with one resin formulation cannot be assumed to apply to another printing material or process.[1, 3, 4]

In a direct comparison, Abdulkarim and Al-Mashhadany found higher light transmittance and lower surface roughness in the tested thermoformed multilayer TPU aligners than in directly printed TC-85 resin aligners.[3] This demonstrates a difference between the two systems evaluated, but does not isolate manufacturing technology as the sole cause. Material chemistry, construction and surface characteristics may also contribute. Similarly, studies of directly printed polyurethane specimens show that cleaning can alter measured roughness and hardness, but because these investigations did not include a matched thermoformed comparator, they establish a response of the tested material rather than a general difference between manufacturing methods.[4] Wali and colleagues examined PET-G, polyurethane and resin-based aligner materials after cleansing-solution exposure, illustrating that mechanical responses can vary among material categories.[5]

3. Effects of cleaning protocols on surface integrity

Surface integrity includes macroscopic roughness, local scratches and finer topographic features. The reviewed studies used profilometry, atomic force microscopy (AFM) and scanning electron microscopy (SEM). These methods examine different surface characteristics and scales; their results should be interpreted as complementary rather than interchangeable measures.[4,6]

Šimunović and colleagues evaluated directly printed polyurethane-based specimens after brushing, brushing with toothpaste, or immersion in a commercial cleaning-tablet solution. Toothpaste-assisted brushing produced the greatest increase in surface roughness, brushing alone also increased roughness, and the tablet group showed a small reduction in measured roughness. Hardness and water absorption also responded differently across protocols.[4] The findings are consistent with mechanical abrasion affecting the tested material, particularly when brushing is combined with toothpaste, but should not be generalised to every resin or toothpaste formulation.

Abdulkarim and Al-Mashhadany compared printed TC-85 resin with thermoformed multilayer TPU after in vitro ageing and repeated cleaning. Surface roughness was lower in the tested thermoformed aligners, while both groups showed heterogeneous features such as pits, dimples, grooves and striations.[3] The results establish differences between these products but cannot determine how much was due to the manufacturing process rather than material formulation.

Yeretsian and colleagues investigated PET-G specimens exposed to mouthwash, cleaning tablets or brushing with toothpaste over 14 days. Profilometry showed an overall difference in macroscopic roughness between groups, including a significant pairwise difference between the mouthwash and control groups. AFM-derived nanoscale parameters also differed across groups; chemically cleaned specimens appeared smoother at the nanoscale, while brushing was associated with localized micro-scratches and irregular features.[6] The divergence between

macroscopic and nanoscale results demonstrates that conclusions may depend on the measurement method and scale.

Clinical evidence likewise does not support the simple assumption that cleaning always increases roughness. In a randomised crossover trial involving 23 participants, Kılıç and colleagues found that unused control aligners had higher measured roughness than cleaned aligners, while the cleaning-crystal group had significantly higher roughness than most other cleaning-agent groups.[7] These results are specific to the tested Invisalign system and protocol.

Huang and colleagues studied thermoplastic orthodontic retainers after coffee staining and cleaning. Mechanical cleaning removed stains but produced linear abrasions; chemical cleaning left visible residues, while ultrasonic cleaning most closely restored the measured surface and optical characteristics to the control condition.[8] Because this study concerned stained retainers rather than routine cleaning of active aligners, it is adjacent evidence and should not be treated as proof of the best protocol for all aligners.

Surface integrity must also be considered alongside cleaning efficacy. Hu and colleagues assessed Streptococcus mutans biofilm removal and material properties in thermoplastic aligner specimens. Toothbrushing and combined cleaning-solution-plus-brushing approaches produced favourable biofilm-removal outcomes, but roughness increased in brushing and combined-treatment groups. Elastic modulus and ultimate tensile strength did not differ significantly between groups.[9] This illustrates a potential trade-off: a protocol may improve biofilm removal while altering surface topography, without a detectable change in the bulk mechanical properties measured.

Overall, the evidence does not support ranking cleaning methods by roughness alone. A smoother surface measurement does not prove superior hygiene, and increased roughness does not by itself establish clinically significant damage or increased biofilm retention. The response depends on material, cleaning protocol, ageing conditions and measurement technique.

4. Effects of cleaning protocols on optical properties

Optical outcomes in the reviewed studies include colour difference (ΔE or ΔE00), translucency-related parameters and light transmittance. These measures are related but not interchangeable: colour difference quantifies a change in colour, whereas translucency and light transmittance describe different aspects of light behaviour. It is also important to distinguish cleaning of initially unstained aligners from cleaning after deliberate staining, because the latter combines stain removal with potential changes to the underlying material.

Fidan and Gelgör compared thermoformed Essix and Scheu materials with directly printed Nexdent aligners of different thicknesses during artificial-saliva ageing and mechanical brushing. The printed group showed lower translucency-related values and greater colour variation than the thermoformed groups; thickness also influenced colour change.[1] These results suggest that product and thickness matter, but do not prove that every printed resin performs less favourably than every thermoforming polymer.

Haliloglu Özkan and colleagues compared Invisalign and ClearCorrect thermoformed aligners, Smartee thermoformed aligners and directly printed 4D Aligners under five cleaning protocols. Colour and translucency-related changes were brand- and protocol-dependent. Invisalign and ClearCorrect showed smaller colour changes than Smartee, while water rinsing and brushing alone produced smaller colour and translucency differences than cleaning-tablet solutions and liquid soap. A significant brand-by-protocol interaction indicated that the effect of cleaning was not uniform across products.[2]

In a separate direct comparison, Abdulkarim and Al-Mashhadany reported greater light transmittance in the tested thermoformed TPU aligners than in the directly printed TC-85 resin aligners across the tested conditions.[3] Together, these comparisons suggest that optical behaviour varies between particular products. Differences in polymer formulation, thickness, ageing conditions and cleaning regimens prevent a simple conclusion that one manufacturing method is inherently superior.

Studies of stained aligners provide a different perspective. Aşık and colleagues examined coffee-stained Invisalign aligners treated with peroxide-containing and peroxide-free cleaning solutions. Cleaning produced partial colour recovery after the initial staining cycle, but a subsequent coffee exposure increased colour difference again. There were no significant overall differences between cleaning groups, although some changes between staining cycles occurred within peroxide-containing groups; the authors also reported associations between solution pH and colour change in peroxide-free groups.[10] These results show that immediate stain removal does not necessarily indicate durable colour stability.

Başal and colleagues evaluated different staining media and cleaning agents. Coffee produced the greatest colour change among the tested beverages, while Corexyl and Cleaning Crystals produced lower ΔE00 values than toothpaste and distilled water. Surface roughness was not significantly affected by cleaning agents in that study and was more closely associated with staining media, with tea and wine producing increases compared with distilled water.[11] This distinction shows that optical improvement does not necessarily correspond to a measurable change in roughness.

In the clinical crossover trial by Kılıç and colleagues, clear soap produced the least colour change in Invisalign aligners, whereas Cleaning Crystals and whitening toothpaste produced the greatest changes among the tested agents.[7] This is clinically relevant for the system studied, but cannot establish how the same agents affect directly printed aligners. Taken together, the evidence indicates that cleaning-related optical changes are material-, brand- and protocol-dependent. Colour recovery, intrinsic colour stability, translucency and light transmittance should be reported separately. Most direct comparisons were conducted in vitro and over limited periods, so they do not establish long-term clinical optical performance or a universally preferred cleaning product.

5. Effects of cleaning protocols on mechanical properties

Mechanical properties relevant to aligner materials include hardness, elastic modulus, elastic recovery, tensile strength and time-dependent stress relaxation. These outcomes describe different material responses. A change in one property should not automatically be interpreted as altered orthodontic force delivery, which also depends on appliance geometry, thickness, fit and loading conditions.

Wali and colleagues assessed PET-G, polyurethane and resin-based materials after exposure to Retainer Brite, Fresh Guard or artificial saliva. Using nanoindentation, they evaluated elastic modulus, hardness, elastic index and load relaxation. The authors reported more pronounced changes after exposure to the peroxide-based cleanser, more moderate changes with Fresh Guard and comparatively minimal effects with artificial saliva. The resin-based material was reported to show greater chemical stability under the tested conditions.[5] These results are specific to the tested products and immersion conditions; they do not establish that every peroxide-containing cleaner affects all aligners similarly.

Šimunović and colleagues found that brushing, with or without toothpaste, increased measured hardness in directly printed polyurethane specimens, whereas Corega treatment decreased hardness. The same study reported surface roughness and water-absorption changes.[4] An increase in hardness should not necessarily be considered an improvement in overall performance, and a decrease does not independently demonstrate clinically relevant loss of force delivery. Nanoindentation measures local material response rather than the performance of the complete appliance.

Stress relaxation describes a reduction in stress over time when a material is maintained at constant deformation. It is relevant to the time-dependent behaviour of orthodontic polymers, but a laboratory stress-relaxation result is not equivalent to a direct measurement of tooth movement or treatment efficiency. Wali and colleagues included load relaxation among their outcomes, highlighting the value of assessing time-dependent behaviour alongside hardness and modulus.[5]

Not all studies detected significant mechanical changes. Hu and colleagues found no statistically significant differences in elastic modulus or ultimate tensile strength after 14 days of brushing, solution soaking, ultrasonic cleaning or combined protocols, despite increased roughness in some brushing groups.[9] Alweneen and Alqahtani assessed Invisalign aligners in an in vivo study involving 12 patients and five cleaning methods. They reported no

significant differences in elastic modulus or Fourier-transform infrared spectroscopy findings between cleaning groups.[12] These results apply to the properties and exposure conditions measured and do not establish that every aspect of material performance remained unchanged.

The differences between studies may reflect material chemistry, cleaning-agent composition, exposure conditions and test methods. Overall, the evidence does not support a universal conclusion that cleaning either degrades or preserves mechanical properties. Future studies should combine material-level tests with appliance-level assessments of force retention under standardised conditions.

The main conclusions of the included studies are summarized in Table 1, which separates studies that looked at a single aligner material or a similar thermoplastic appliance from direct comparisons of production techniques.

Table 1. Evidence synthesis of cleaning-related changes in clear aligners and related thermoplastic orthodontic appliances

Study	Material / study design and cleaning exposure	Outcomes assessed	Principal findings and interpretation
Fidan and Gelgör [1]	Thermoformed Essix/Scheu and directly printed Nexdent aligners; ageing and mechanical brushing; different thicknesses.	Colour stability and translucency.	Printed aligners showed lower translucency and greater colour variation in the tested conditions. Manufacturing route, material and thickness should be considered together; the result is not a universal ranking of all printed and thermoformed systems.
Haliloglu Özkan et al. [2]	Thermoformed Invisalign and ClearCorrect, thermoformed Smartee and directly printed 4D Aligners; five cleaning protocols.	Colour and translucency-related optical measures.	Optical responses varied by brand and cleaning protocol. Water rinsing or brushing alone generally produced smaller changes than some tablet and liquid-soap protocols in the tested conditions. Findings are limited to the products, exposures and optical outcomes assessed.
Abdulkarim and Al-Mashhadany [3]	Directly printed TC-85 resin compared with thermoformed multilayer TPU; in-vitro ageing and cleaning.	Optical properties, surface morphology and roughness.	The tested thermoformed TPU showed higher transmittance and lower roughness than the tested printed resin. Because polymer chemistry and manufacturing route differed together, the effects cannot be attributed to manufacturing method alone.
Šimunović et al. [4]	Directly printed polyurethane-based specimens; brushing, toothpaste-assisted	Roughness, hardness and water absorption	Toothpaste-assisted brushing produced the largest roughness increase in the tested conditions. Tablet

	brushing and cleaning-tablet immersion.	/ physical properties.	treatment reduced measured hardness and altered water absorption. These laboratory findings are material- and protocol-specific.
Wali et al. [5]	PET-G, polyurethane and resin-based aligner materials exposed to cleansing solutions and artificial saliva.	Nanoindentation-based mechanical properties.	Measured responses differed among material categories and solutions; peroxide-based cleaner produced stronger changes in some measured properties, while artificial saliva generally produced smaller changes. The study does not establish a single safest cleaner for every commercial aligner.
Yeretsian et al. [6]	PET-G specimens exposed to mouthwash, cleaning tablets and toothpaste-assisted brushing over 14 days.	Profilometry and AFM / nanoscale topography.	Surface findings depended on the scale and method of measurement. Brushing could produce nanoscale scratches, while some chemical treatments appeared smoother at that scale; profilometric and AFM findings should not be treated as interchangeable.
Kılıç et al. [7]	Invisalign aligners in a randomised crossover clinical study (23 participants); clear soap, Cleaning Crystals and whitening toothpaste among tested methods.	Colour change and surface roughness.	Clear soap produced the least colour change, while Cleaning Crystals and whitening toothpaste produced greater changes among the tested protocols. Roughness did not follow a simple, uniform pattern across methods.
Huang et al. [8]	Coffee-stained thermoplastic orthodontic retainers; brushing, chemical cleaning and ultrasonic treatment.	Surface roughness and optical properties.	Ultrasonic treatment most closely restored some measured surface and optical outcomes in the tested retainer model; brushing produced abrasions and chemical treatment could leave residues. This is adjacent evidence from retainers, not direct evidence for all active aligners.
Hu et al. [9]	Thermoplastic aligner materials; brushing, soaking, ultrasonic and combined cleaning protocols.	Streptococcus mutans biofilm removal, roughness, elastic modulus and ultimate tensile strength.	Some brushing-based and combined protocols improved biofilm removal but increased roughness. Elastic modulus and ultimate tensile strength did not differ significantly between groups, illustrating that hygiene efficacy and

			surface preservation are distinct outcomes.
Aşık et al. [10]	Coffee-stained Invisalign aligners treated with different cleaning protocols.	Colour improvement and colour stability / restaining.	Cleaning produced partial colour improvement, but staining could recur. Differences between cleaning methods were not uniformly significant, so colour recovery should not be interpreted as durable prevention of restaining.
Başal et al. [11]	Clear aligners exposed to different staining media and cleaning agents.	Colour difference (ΔE00) and surface roughness.	Coffee caused the greatest colour change among tested beverages. Corexyl and Cleaning Crystals produced lower ΔE00 than toothpaste and distilled water in the tested conditions; roughness was more closely associated with staining media than with cleaning agents.
Alweneen and Alqahtani [12]	In-vivo study of Invisalign aligners in 12 patients using five cleaning methods.	Elastic modulus and FTIR chemical analysis.	No significant between-group differences were detected in elastic modulus or FTIR findings. These measured outcomes do not establish that all optical, surface or mechanical characteristics remain unchanged during use.

Abbreviations: *AFM, atomic force microscopy; FTIR, Fourier-transform infrared spectroscopy; PET-G, polyethylene terephthalate glycol-modified; TPU, thermoplastic polyurethane. Studies of retainers are identified as adjacent evidence. Differences across studies in materials, exposure conditions and outcome measures preclude a universal ranking of cleaning protocols.*

6. Clinical implications: balancing cleaning efficacy and material preservation

Cleaning has two related but distinct aims: reducing biofilm and deposits, and preserving surface, optical and mechanical characteristics. A protocol that performs well for one aim cannot automatically be considered optimal overall. Hu and colleagues reported improved S. mutans removal with some brushing-based protocols alongside increased roughness, while elastic modulus and tensile strength did not differ significantly.[9] Conversely, Šimunović and colleagues observed increased roughness with toothpaste-assisted brushing and changes in hardness and water absorption after tablet treatment in printed polyurethane specimens.[4]

Optical studies also show that the effect of cleaning varies by product and outcome. Some protocols partially remove existing stains, but subsequent staining may recur; colour change and translucency should not be treated as the same endpoint.[2,10,11] A finding in one aligner brand cannot be assumed to apply to a different printed resin or thermoformed polymer.

The available evidence therefore supports three separate questions when evaluating a cleaning protocol: (1) does it reduce biofilm, deposits or staining; (2) does it measurably alter the surface, optical or mechanical properties; and (3) are those changes large enough to affect hygiene, appearance, fit, durability or orthodontic performance? The reviewed studies answer these questions to differing degrees, and none establishes a protocol that optimises all outcomes for both printed and thermoformed aligners.

In practice, cleaning should be effective without unnecessary abrasion or unvalidated chemical exposure. However, the evidence does not justify a blanket recommendation against brushing or chemical cleaning, because effects vary by material and protocol. Material-specific manufacturer guidance should be considered, and laboratory changes should not be presented as proof of clinical harm unless a clinically meaningful relationship has been demonstrated.

7. Research gaps and future directions

The main evidence gap is the limited number of controlled comparisons that test directly printed and thermoformed aligners under identical conditions. Existing comparisons often involve different commercial formulations, thicknesses or constructions, so manufacturing method cannot be isolated reliably.[1–3] Future studies should compare multiple materials from both categories using matched cleaning protocols and should report composition, thickness and processing details.

Cleaning methods also vary in agent composition, concentration, exposure duration, frequency, brushing force and ultrasonic settings. This heterogeneity restricts comparison across studies. Standardised protocols should include untreated controls, clinically relevant reference methods and repeated cycles that approximate actual use.[4,6]

Most laboratory studies cannot reproduce the full oral environment, including saliva, temperature fluctuations, dietary staining, biofilm and repeated insertion and removal. Longer-term clinical studies should complement laboratory testing and evaluate whether observed changes persist during use. The clinical studies by Kılıç and by Alweneen and Alqahtani provide useful models, but broader replication across material systems is needed.[7, 12]

Outcome measures should also be harmonised. Profilometry and AFM assess different surface scales; ΔE and ΔE00, translucency parameters and light transmittance are not interchangeable; and hardness, elastic modulus, tensile strength and stress relaxation describe distinct mechanical properties. Studies should report effect sizes and uncertainty, not only statistical significance, and use complementary methods where feasible.[6]

Most importantly, future research should connect material measurements to clinical outcomes. Surface roughness should not be treated as proof of increased biofilm retention without microbiological assessment, and a change in hardness should not be equated with altered force delivery. Studies should assess biofilm removal, staining, optical performance, surface condition and mechanical behaviour together, and investigate clinically meaningful thresholds rather than infer them from statistical significance alone.[9]

Directly printed aligners warrant material-specific evaluation because photopolymerisable resins are not a uniform category. Detailed reporting of resin identity, printing parameters, post-processing and ageing conditions, alongside chemical characterisation before and after cleaning, would help test proposed mechanisms rather than infer them from surface appearance alone.[3,4] Overall, research should move from detecting isolated laboratory changes towards establishing whether a protocol maintains hygiene while preserving the performance of a specific aligner throughout its intended use.

8. Conclusion

Cleaning protocols can influence the surface integrity, optical characteristics and mechanical properties of clear aligners, but the nature and magnitude of these changes vary with material composition, commercial product, cleaning method and assessment technique. Current evidence does not support a universal conclusion that directly 3D-printed aligners are consistently more or less resistant to cleaning-induced changes than thermoformed aligners.

Direct comparisons demonstrate differences between particular printed and thermoformed systems, but formulation, thickness and construction may contribute to these findings. Brushing, chemical immersion and combined protocols can produce different responses, and laboratory changes do not necessarily indicate clinically significant deterioration. Cleaning efficacy must therefore be assessed alongside material preservation.

Within the limitations of the evidence, cleaning strategies should be material-specific and aim to achieve effective hygiene while avoiding unnecessary material alteration. Standardised comparative studies and longer-term clinical

investigations are required to determine whether measured surface, optical and mechanical changes affect appliance performance and to support evidence-based cleaning recommendations.

9. References

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