

Effect of cigarette smoking and alcohol consumption on the colour stability of various orthodontic aligners—an in vitro study

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Aim: The present study aimed to analyse and compare the colour stability of three types of orthodontic clear aligners following in vitro exposure to cigarette smoking and alcohol by using the attenuated total reflectance-Fourier transform infrared spectroscopy (ATR-FTIR) method.

Materials and methods: The study included 144 clear aligners divided into 3 groups of 48 each based on different manufacturers and comprised: Group A—Invisalign, Group B—Kiyoclear, Group C—OrthoFX. The samples were tested for colour stability related to translucency after exposure to cigarette smoke and alcoholic drinks at times, T0: before exposure (as-received aligner), T1: after a seven-day exposure, T2: after a fourteen-day exposure using the ATR-FTIR method. Data were analysed using one-way ANOVA, Tukey's post hoc test, Repeated Measures of ANOVA, Bonferroni's post hoc test, and Independent Student's *t* test accepting a *p*-value < 0.05.

Results: There was a statistically significant difference in the mean translucency values between the three groups at T0, T1, and T2. All groups exhibited mean translucency values which significantly decreased over time following smoking and alcohol exposure.

Conclusion: OrthoFX, Kiyoclear and Invisalign showed decreasing translucency values following smoking and alcohol exposure, with smoking causing a greater reduction. Both types of exposure should be avoided to maintain an aesthetic orthodontic appearance.

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Introduction

Clear aligner treatment (CAT) has an increasing prevalence in orthodontics, as advancements in biomaterials, design and engineering lead to its adoption as a suitable appliance in managing mild to moderate malocclusions.¹ The most significant advantage of clear aligners is their increased comfort and convenience, allowing easy removal while eating,

cleaning, and flossing.² The CAT process is based on the sequential use of aligners made of thermoplastic materials which include, polyethylene terephthalate glycol (PETG), polyethylene terephthalate (PET), polyurethane (PU), or polyvinyl chloride (PC).^{3,4} The limitations of these thermoplastic materials include dimensional instability, low resistance to wear and

mastication, and aesthetic changes resulting from water or food colourant absorption.⁵

Compliance with CAT guidelines is essential for successful treatment, which requires each set of aligners to be worn for at least 22 hours daily, over 1 to 2 weeks as non-compliance may prolong therapy or cause failure.⁶ Instructions to remove aligners before eating and drinking during treatment are contentious since studies have demonstrated low patient compliance and concern among orthodontists.⁷

As a result, the aligner will inevitably be exposed to mechanical operations, heat, humidity, food components, salivary enzymes, and colouring agents leading to biofilm deposits, material delamination, micro-cracks, and abrasions producing severe mechanical strength and transparency loss thereby putting the patient at a disadvantage.⁸

Similarly, smoking tobacco and consuming alcohol are prevalent lifestyle issues potentially causing addiction among young adults who are also potential candidates for clear aligner therapy.⁹

To maintain appliance aesthetics, the colour and transparency of clear aligners should remain consistent throughout their intraoral use, regardless of compliance.¹⁰ However, without removing the appliances, users frequently expose aligners to hazardous and staining chemicals, particularly by smoking or drinking.

Although clear aligners are becoming more prevalent, there has been little research on their aesthetic stability. Several *in vitro* studies have investigated the colour stability and mechanical qualities of aligner materials subjected to various staining agents.^{5,11} The present study intends to investigate the reaction of aligners to cigarette smoke and alcohol consumption over time by examining aligner materials in clinical situations and to thereby inform orthodontists and patients about material selection and maintenance.

Therefore, the present study aimed to examine and contrast the colour stability of three different brands of orthodontic clear aligners and their respective materials following exposure to alcohol and cigarette smoke *in vitro*.

Materials and methods

The study was approved by Sri Rajiv Gandhi College of Dental Science and Hospital Bangalore's

Institutional Ethics Committee (IEC) (IEC No. SRGCDs/2024/106).

The study involved 144 clear aligners, divided into three groups according to the providing manufacturers.

Group A—Invisalign (INV) (Align Technology Inc., San Jose, CA, USA)—48 appliances of which 24 were exposed to smoke from cigarettes and 24 were exposed to alcohol.

Group B—Kiyo Clear (Kiyo Dental Co., Ltd., Tokyo, Japan) 48 appliances of which 24 were exposed to smoke from cigarettes and 24 were exposed to alcohol.

Group C—OrthoFX (OrthoFx, Inc., Fremont, CA, USA) 48 appliances of which 24 were exposed to smoke from cigarettes and 24 were exposed to alcohol.

SmartTrack material, which is a multi-layered thermoplastic polyurethane with an incorporated elastomer, is used in the formation of INV appliances.^{12,13} Other thermoplastic materials like PETG, PET, PU, and PC are widely used in the fabrication of other brands such as KiyoClear and OrthoFX due to their technical properties.¹⁴

The collected samples were exposed to cigarette smoke and alcoholic drinks to assess the colour stability by investigating the translucency of the aligners using a Fourier-transmitted infrared spectrometer. The null hypothesis was that cigarette smoke and alcohol consumption had no significant influence on the material's characteristics.

While there are several ways to produce smoke for *in vitro* experiments,¹⁵ a full smoke approach was used in the current study. The simulation involved a smoking chamber housing a plastic container that was first compressed to draw in external air through an aperture to which a cigarette would be connected (Figure 1).

The average number of cigarettes smoked by an adult in an urban zone has been reported to be 10 cigarettes per day,¹⁶ therefore 24 aligners from each group were exposed to 10 cigarettes per day for 7 days [T1] and 14 days [T2].

Similarly, a second set of 24 aligners from each group were exposed to an alcoholic drink (Whiskey). The specimens were immersed in a glass jar containing 250 mL of whiskey (Johnnie Walker Red Label)



Figure 1. Whole smoke approach.

and kept in a closed container for 20 minutes/day at room temperature. It has been reported that 50% of American adults consume various non-alcoholic beverages which comprise an average of 3.2 cups per day and drinking each cup over a 15 minute time period for 7 days [T1] and 14 days [T2]^{17,18} (Figure 2).

The optical properties of each aligner, related to translucency, were investigated by attenuated total reflectance-Fourier transform infrared spectroscopy (ATR-FTIR) measurements carried out utilising an ALPHA spectrophotometer (model ALPHA, BRUKER, Germany), at a range of 500 to 7500 cm^{-1} and a resolution of 2 cm^{-1} (Figure 3) at times T0, T1, and T2 (for 7d and 14d separately).

T0: before exposure (as-received aligner).

T1: after a seven-day exposure.

T2: after a fourteen-day exposure.



Figure 2. Glass jar with specimens immersed in 250ml of whiskey.

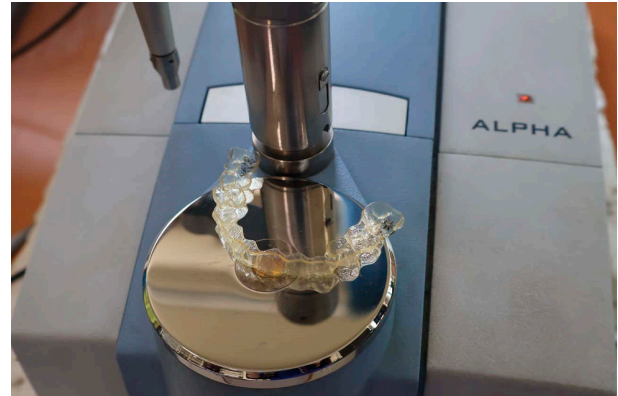


Figure 3. ALPHA spectrophotometer (model ALPHA, BRUKER, Germany).

A total of 144 aligners were scanned at T0, T1 and T2 to acquire a translucency index.

Statistical analysis

A statistical analysis of the obtained data was performed using SPSS software (SPSS for Windows version 20.0; SPSS Inc, Chicago, IL, USA). Descriptive and comparison statistics were generated for the assessed parameters. Data was analysed using, one-way ANOVA, Tukey's post hoc test, Repeated Measures of ANOVA, Bonferroni's post hoc test, and Independent Student's *t* test. Statistical significance was set at $p < 0.05$.

Results

The study involved 144 clear aligners from the three groups, Invisalign, Kiyoclear, and OrthoFX, to evaluate their translucency before and after exposure to alcohol and cigarette smoke. At baseline [T0], the three groups showed a significant difference in the mean translucency values.

The repeated analysis of mean baseline period translucency values revealed no statistically significant variance between Invisalign and Kiyoclear ($p = 0.54$). However, the study discovered significant variations between Invisalign and OrthoFX ($p = 0.001$) and Kiyoclear and OrthoFX ($p = 0.03$) (Figure 4) (Table I).

After 7 days of exposure to cigarette smoke [T1], the three groups showed statistically significant differences in mean translucency values.

The repeated comparison of mean differences revealed a statistically significant distinction between

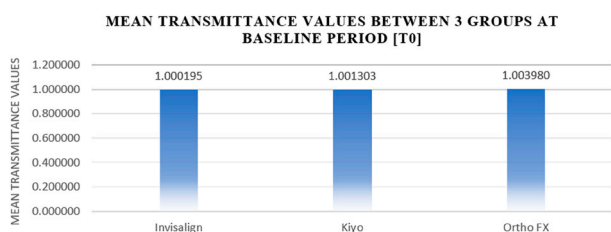


Figure 4. Mean transluency values between the 3 groups at baseline (T0).

Invisalign and KiyoClear ($p = 0.001$). Nevertheless, there was no statistically significant distinction between Invisalign and OrthoFX ($p = 0.14$). Finally, Kiyo and OrthoFX showed a substantial difference ($p < 0.001$) (Figure 5) (Table I).

Similarly, following 14 days of cigarette smoke exposure, there was a statistically significant reduction in the mean transluency values between the three groups [T2] ($p = 0.005$) [Table I].

Multiple evaluations of mean differences at [T2] showed a substantial difference between Invisalign and KiyoClear. In addition, there was no noticeable difference between KiyoClear and OrthoFX compared to Invisalign. This suggests that Kiyo displayed the greatest mean transluency value,

followed by OrthoFX and finally Invisalign after 14 days of smoking exposure (Figure 6).

After 7 days of alcohol exposure [T1] there was a statistically significant difference in the mean transluency values between the three groups ($p = 0.005$).

The multiple comparisons of mean differences indicated that there was a significant difference between Invisalign and KiyoClear but there was no significant difference between Invisalign and OrthoFX. Lastly, there was a significant difference between KiyoClear and OrthoFX which implied that KiyoClear demonstrated the highest mean transluency value at 7 days of alcohol exposure, followed by Invisalign and OrthoFX (Figure 7) (Table II).

Similarly, following 14 days of alcohol exposure [T2], the three groups showed a statistically significant variation in mean transluency values ($p < 0.001$).

Multiple comparisons of mean differences demonstrated a substantial difference comparing Invisalign and KiyoClear, as well as between Invisalign and OrthoFX. Furthermore, there was a significant variation between Kiyo and OrthoFX, implying that KiyoClear displayed the greatest mean

Table I. Comparison of mean Transmittance values between 3 groups at baseline period [T0]

Groups	N	Mean	SD	Min	Max	p-value ^a	Sig. Diff	p-value ^b
Invisalign	24	1.000195	0.004414	0.99295	1.00679	0.002*	I vs K	0.54
Kiyo	24	1.001303	0.002702	0.99889	1.00679		I vs O	0.001*
Ortho FX	24	1.003980	0.003455	0.99889	1.00875		K vs O	0.03*
Comparison of mean Transmittance values between 3 groups at 7 Days of Smoking Exposure [T1]								
Groups	N	Mean	SD	Min	Max	p-value ^a	Sig. Diff	p-value ^b
Invisalign	24	0.996308	0.000205	0.99591	0.99662	0.001*	I vs K	0.001*
Kiyo	24	0.997270	0.001034	0.99557	0.99949		I vs O	0.14
Ortho FX	24	0.995812	0.001120	0.99412	0.99718		K vs O	<0.001*
Comparison of mean Transmittance values between 3 groups at 14 Days of Smoking Exposure [T2]								
Groups	N	Mean	SD	Min	Max	p-value ^a	Sig. Diff	p-value ^b
Invisalign	24	0.990903	0.000923	0.99006	0.99222	0.005*	I vs K	0.007*
Kiyo	24	0.991858	0.001258	0.99006	0.99634		I vs O	0.03*
Ortho FX	24	0.991700	0.000947	0.99006	0.99444		K vs O	0.86

One-way ANOVA Test followed by Tukey's post hoc Test.

$P < 0.05^*$ — Statistically significant.

^aComparison of mean transmittance values between three groups.

^bMultiple comparison of mean differences in transmittance values among the three groups.

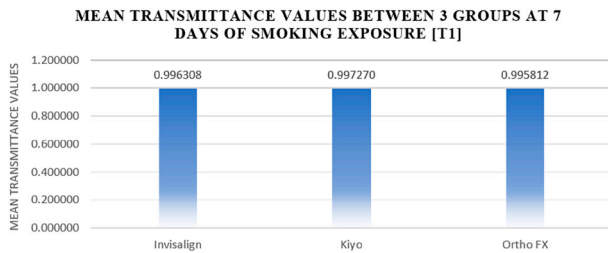


Figure 5. Mean translucency values between the 3 groups after 7 days of smoking exposure (T1).

translucency value, followed by OrthoFX and finally Invisalign after 14 days of alcohol exposure [T2] (Figure 8) (Table II).

The study found that the mean translucency values significantly decreased over time following smoking exposure and alcohol exposure, with significant differences observed between the time intervals. This indicated considerable variation in translucency values within each group throughout the exposure period. The results also indicated considerable variation in translucency values within each group (Figures 9 and 10) (Table III).

Over time, all groups exhibited decreasing mean translucency values following smoking and alcohol exposure. However, the impact of smoking exposure was more pronounced compared to alcohol exposure over the different time intervals.

Discussion

A revolution has resulted from a growing patient desire for aesthetically pleasing orthodontic appliances which incorporate invisible options in the form of clear aligners, lingual appliances, and cosmetic brackets. For comfort and cosmetic reasons, adults frequently choose transparent aligners over fixed appliances.¹⁹

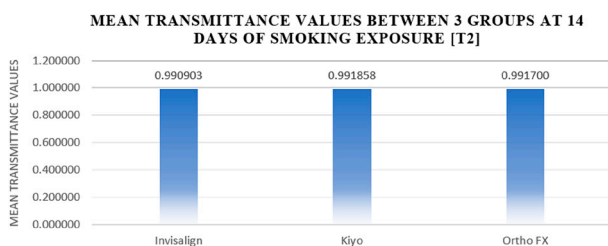


Figure 6. Mean translucency values between the 3 groups after 14 days of smoking exposure (T2).

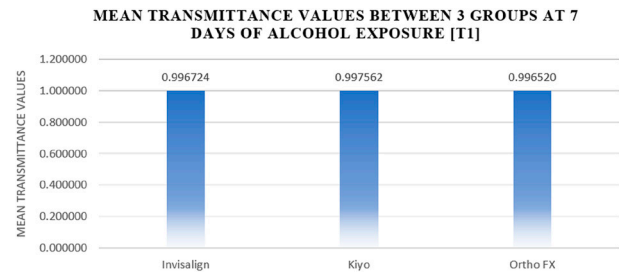


Figure 7. Mean translucency values between the 3 groups after 7 days of alcohol exposure (T1).

The clear aligner treatment process involves sequentially using transparent thermoplastic materials, which include PETG, PET, PU, and PC, to fabricate the appliances.⁴

Much research has investigated the mechanical characteristics of clear aligners, especially their biomechanics during orthodontic therapy, as well as new materials with desired mechanical properties for orthodontic treatment. The aesthetic reliability of these materials has not been extensively researched, despite their usefulness as aesthetic appliances.²⁰

Aligners are susceptible to discolouration when used in the oral cavity, especially when patients drink alcohol or smoke cigarettes without removing the appliances. Patients who do not follow the instructions provided at the commencement of aligner therapy may accumulate staining agent pigments, causing colour changes in aligner materials, and a loss of transparency thereby making clear aligners less appealing even over a 2-week treatment period.²¹

Therefore, the present study aimed to explore the colour stability related to the translucency of three commonly used aligner materials by exposure to cigarette smoke and alcohol which are considered to be prevalent lifestyle issues causing addiction among young adults who are also potential candidates for clear aligner therapy. The results were expected to provide evidence for patients and orthodontists regarding clinical aesthetics and instructions.

The FT-IR results indicated that the three groups of aligners Invisalign, KiyoClear, and OrthoFX, when exposed to alcohol and cigarette smoke, exhibited significant differences in mean translucency values under the tested conditions and time intervals. The values varied significantly between the three groups, indicating considerable differences in translucency at the outset.

Table II. Comparison of mean Transmittance values between 3 groups at 7 Days of Alcohol Exposure [T1]

Groups	N	Mean	SD	Min	Max	p-value ^a	Sig. Diff	p-value ^b
Invisalign	24	0.996724	0.000660	0.99591	0.99843	0.001 *	I vs K	0.01 *
Kiyo	24	0.997562	0.001100	0.99619	0.99954		I vs O	0.76
Ortho FX	24	0.996520	0.001157	0.99432	0.99865		K vs O	0.002 *
Comparison of mean Transmittance values between 3 groups at 14 Days of Alcohol Exposure [T2]								
Groups	N	Mean	SD	Min	Max	p-value ^a	Sig. Diff	p-value ^b
Invisalign	24	0.991773	0.000469	0.99089	0.99241	<0.001 *	I vs K	<0.001 *
Kiyo	24	0.992523	0.000303	0.99211	0.99293		I vs O	0.02 *
Ortho FX	24	0.992131	0.000573	0.99089	0.99293		K vs O	0.01 *

One-way ANOVA Test followed by Tukey's post hoc Test.

$P < 0.05$ * — Statistically significant.

^aComparison of mean transmittance values between three groups.

^bMultiple comparison of mean differences in transmittance values among the three groups.

The colour changes of clear aligners may be linked to pigment adsorption or material surface penetration when immersed in alcohol. The chemical makeup of the aligner materials and the staining pigments in the exposed agents might be connected to this process.^{22,23}

In comparison, Liu et al. evaluated the colour stability of three distinct types of clear aligners that were exposed to colouring agents such as coffee, black tea, and red wine and observed that the aligners had colour stability for the first 12 hours, after which they displayed more pronounced colour changes as the immersion period increased to seven days.⁵

In the present study, the differences in translucency between the three aligners may be due to their different polymer-based materials, which may have varying staining agent susceptibilities. Similarly, earlier studies revealed that polyurethane-based orthodontic retainers and ligatures are vulnerable to pigment adsorption and lack colour stability,

with obvious colour changes following contact with staining agents.^{24,25} However, polyvinyl chloride-based aesthetic wires were found to maintain high levels of colour stability.²²

The present study showed changes in translucency after exposure to cigarette smoke which were also significant between the three groups. Similarly, Copello et al. found that exposure to cigarette smoke can alter mechanical characteristics like friction and the optical properties of aesthetic orthodontic wires.²⁵ Arthur et al. explained this mechanical deterioration was likely due to chemical discolouration, oxidation in the polymer matrix, and degradation products from water diffusion or polymer oxidation.²⁶

In the present study, all groups exhibited decreasing mean translucency values following smoking and alcohol exposure. However, the impact of smoking exposure was more pronounced compared to alcohol exposure over the different time intervals.

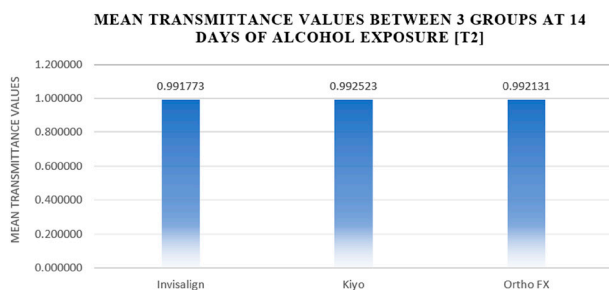


Figure 8. Mean translucency values between the 3 groups after 14 days of alcohol exposure (T2).

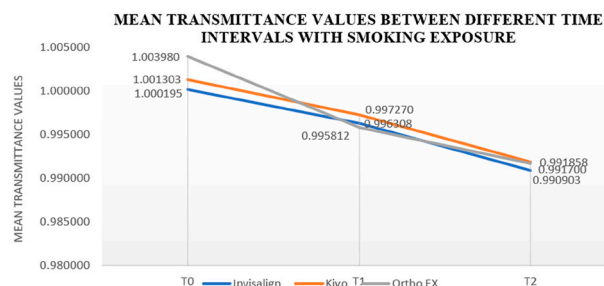


Figure 9. Mean translucency values between the different time intervals following smoking exposure.

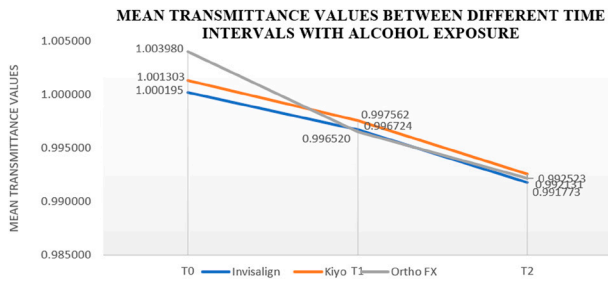


Figure 10. Mean translucency values between the different time intervals following alcohol exposure.

Specifically, for the Invisalign group, the mean translucency values decreased significantly more from smoking exposure than from alcohol exposure at both the 7 day and 14 day intervals. This pattern was also observed in the OrthoFX group, in which smoking had a greater reduction effect on translucency values compared to alcohol.

In contrast, the KiyoClear group showed similar trends of decreasing translucency values over time, but the differences between smoking and alcohol exposure were not as pronounced. This suggested that both exposures had a relatively similar impact on the translucency values of the KiyoClear group.

The current study's findings were found to be consistent with those of Liu et al. who demonstrated that the Invisalign aligners made of polyurethane showed noticeably higher colour change values than those made from polyethylene terephthalate glycol and polyvinyl chloride.⁵

Overall, the results highlight that smoking exposure generally leads to a greater reduction in translucency values compared to alcohol exposure. The time-dependent nature of these changes underscores the

importance of considering both the type of exposure and its duration when assessing the impact. OrthoFX consistently showed the highest mean translucency values over the different periods and conditions, followed by KiyoClear and Invisalign.

The present study was an in vitro experiment that did not mimic natural oral scenarios, particularly saliva exposure. The findings should be carefully analysed to determine the level of translucency change in the intraoral analogues because, simple exposure tests may contribute to premature deterioration of aligner translucency, thereby reducing the colour stability.

However, patients should be advised to remove the aligners before eating, smoking, and drinking to maintain colour stability, protect the material's mechanical properties, and ensure proper care and aesthetics.

Further research is needed to improve the colour stability and mechanical properties of aligner materials, as pigment adsorption is linked to polymer surface polar groups and surface roughness.

Conclusion

As aesthetic orthodontic appliances, the three groups of clear aligners exhibited decreasing mean translucency values following both smoking and alcohol exposure over time. Smoking exposure led to a greater reduction in translucency values than alcohol exposure, with Ortho FX showing the highest mean translucency values across the different time periods and conditions, followed by KiyoClear and Invisalign. The time-dependent nature of these changes underscores the significance of considering both types of exposure.

Table III. Comparison of mean Transmittance values between Smoking & Alcohol Exposure in each group at 7 Days' time interval using

Groups	Exposure	N	Mean	SD	Mean Diff.	p-value
Invisalign	Smoking	24	0.996308	0.000205	-0.000417	0.005*
	Alcohol	24	0.996724	0.000660		
Kiyo	Smoking	24	0.996603	0.001253	-0.000583	0.13
	Alcohol	24	0.997187	0.001370		
Ortho FX	Smoking	24	0.995812	0.001120	-0.000708	0.04*
	Alcohol	24	0.996520	0.001157		

Independent Student's *t* test.

P < 0.05* — Statistically significant.

Conflict of interest

The authors declare that there is no conflict of interest.

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