

Augmented Reality (AR) as an Educational Tool for Fixed Orthodontic Treatment to Improve Adolescent Patient Compliance

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ABSTRACT

Adolescent compliance during fixed orthodontic treatment encompassing oral hygiene behavior, appointment attendance, and adherence to instructions is often poor, contributing to prolonged treatment, white spot lesions, and bracket bond failure. This single-blind, parallel-group randomized controlled trial evaluated whether a smartphone-based augmented reality (AR) educational application, added to standard chairside instruction, improves compliance-related outcomes compared with conventional education alone. A total of 120 adolescents (12–17 years) beginning fixed orthodontic treatment were randomized 1:1 to an AR education group (n=60) or a conventional education group (n=60) and assessed at baseline, 6, 12, and 24 weeks. At 24 weeks, the AR group showed lower Plaque Index (0.81 vs. 1.42; Cohen's $d=3.05$, $p<0.001$) and Gingival Index (0.68 vs. 1.31; $d=3.42$, $p<0.001$), higher orthodontic care knowledge on a 0–100% scale (89.4% vs. 68.7% immediately post-intervention; $d=2.70$, $p<0.001$), higher appointment attendance (96.2% vs. 87.4%, $p<0.01$), lower bracket bond failure rate (4.8 vs. 9.6 per 100 patient-months, $p<0.01$), and greater reduction in dental anxiety (MCDASf 10.8 vs. 13.1 at 6 weeks; $d=0.84$, $p<0.001$). The application achieved excellent usability (System Usability Scale 82.4 ± 7.8). These findings suggest AR may be a promising adjunct for improving adolescent compliance during fixed orthodontic treatment, although confirmation in multi-center trials with longer follow-up is needed.

INTRODUCTION

Fixed orthodontic appliances remain the most widely used treatment modality for correcting malocclusion, yet the presence of brackets, bands, and archwires substantially complicates mechanical plaque removal and creates numerous plaque-retentive sites. Without adequate patient compliance, this can result in white spot lesion formation, gingival inflammation, prolonged treatment duration, and repeated bracket bond failure, all of which compromise both treatment outcomes and cost-effectiveness (Shah et al., 2025).

Adolescent patients, who constitute the majority of the fixed orthodontic treatment population, present particular compliance challenges. This age group is characterized by evolving autonomy, competing academic and social priorities, and variable intrinsic motivation for sustained self-care behaviors, and prior research has consistently identified adolescents as having the poorest oral hygiene compliance among orthodontic patients, with a marked decline typically observed shortly after appliance placement (Farhadifard et al., 2020). Conventional patient education strategies verbal chairside instruction supplemented by printed pamphlets - have shown only modest and often short-lived effects on compliance-related outcomes in this population (Al-Abdallah et al., 2021).

In response to these limitations, digital and interactive educational interventions have been increasingly investigated as adjuncts to conventional orthodontic patient education. Smartphone applications incorporating reminders, gamification, and social-media-style engagement have demonstrated measurable improvements in plaque control and gingival health among adolescent orthodontic patients (Farhadifard et al., 2020; Deleuse et al., 2020). However, most existing digital tools rely on two-dimensional video or static content, which may not fully convey the three-dimensional, procedural nature of oral hygiene techniques around complex fixed-appliance components such as archwires, ligatures, and interproximal spaces.

Augmented reality (AR) the real-time overlay of interactive digital content onto the physical environment - offers a fundamentally different visualization paradigm. By allowing patients to view an interactive three-dimensional model of their own dentition and appliance, with animated demonstrations of correct brushing angles, interdental brush placement, and simulated tooth movement, AR has the potential to bridge the gap between abstract verbal instruction and the concrete manual skill required for effective oral hygiene around fixed appliances (Fahim et al., 2022). AR has already demonstrated clinical utility in orthodontics for bracket positioning navigation and cephalometric visualization (Lo et al., 2021), and has been highlighted as a promising direction for simulation-based orthodontic education more broadly (Sipiyaruk et al., 2023).

Beyond orthodontics, AR-based mobile educational tools have shown favorable learning outcomes and high user acceptance in other dental education contexts, such as AR-guided tooth carving training for dental students, which improved both accuracy and learner confidence relative to conventional plastic-model practice (Lim et al., 2023). Similarly, broader reviews of AR and VR applications in dentistry have highlighted their capacity to reduce patient anxiety and enhance comprehension of treatment procedures through immersive, patient-specific visualization (Fahim et



al., 2022; Rosu et al., 2025). Despite this growing evidence base, direct empirical evaluation of AR specifically as a patient-facing educational and motivational tool for improving adolescent compliance during fixed orthodontic treatment as opposed to AR's use in clinician training or intraoperative navigation - remains limited (Shah et al., 2025).

The objective of this study was therefore to evaluate the effectiveness of a smartphone-based AR educational application, used as an adjunct to standard chairside oral hygiene instruction, on oral hygiene status (Plaque Index, Gingival Index), orthodontic care knowledge, appointment attendance, bracket bond survival, and dental anxiety among adolescent patients undergoing fixed orthodontic treatment, compared with conventional education alone, and to assess the usability of the AR application from the patient's perspective.

METHODS

1. Study Design and Ethics

This study was designed as a single-blind, parallel-group randomized controlled trial conducted at a university-affiliated orthodontic clinic. Ethical approval was obtained from the Institutional Research Ethics Committee, and written informed consent/assent was obtained from parents/guardians and adolescent participants prior to enrollment. The clinical examiners assessing Plaque Index, Gingival Index, and bracket bond failure were blinded to group allocation.

2. Participants and Sample Size

Adolescent patients aged 12-17 years beginning comprehensive fixed orthodontic treatment with pre-adjusted edgewise appliances were consecutively screened. Inclusion criteria were good general health, no periodontal disease, and access to a compatible smartphone; exclusion criteria were craniofacial syndromes, cognitive or visual impairment precluding AR use, prior orthodontic treatment, and current antibiotic or anti-inflammatory medication use. Based on an expected between-group difference in Plaque Index of 0.4 (SD 0.6, $\alpha = 0.05$, power = 0.80), a minimum of 54 participants per group was required; 60 per group ($n = 120$) were enrolled to allow for attrition. Of 156 adolescents assessed, 36 were excluded (22 ineligible, 14 declined), leaving 120 randomized participants; flow through enrollment, allocation, follow-up, and analysis is summarized in the CONSORT diagram (Figure 1).

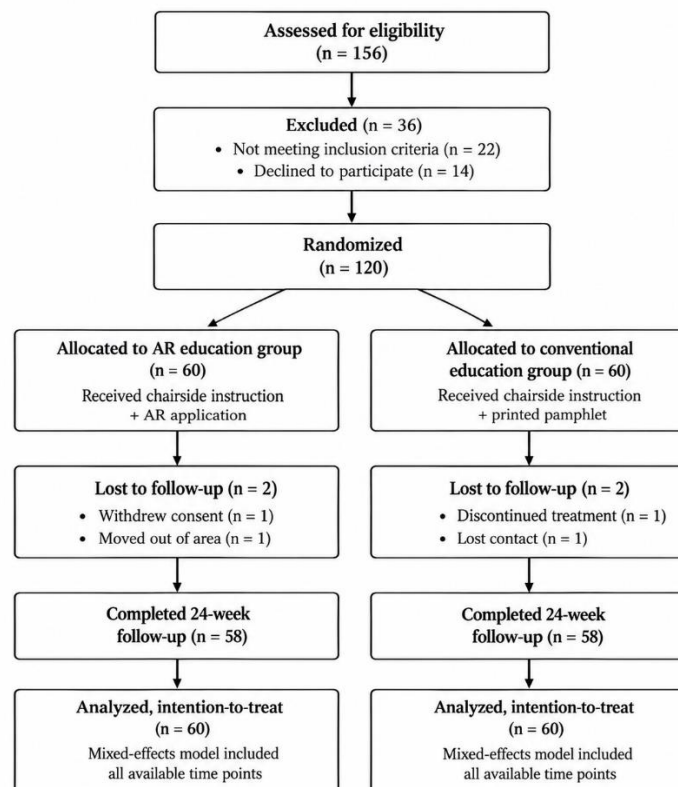


Figure 1. CONSORT flow diagram of participant screening, randomization, allocation, follow up, and analysis.

3. Randomization and Blinding

Participants were allocated 1:1 to the AR or conventional education group using computer-generated block randomization (block size of 4), generated by an independent biostatistician with no role in recruitment, treatment, or outcome assessment. Allocation concealment used sequentially numbered, sealed, opaque envelopes prepared by the same biostatistician and opened by a research assistant, only after baseline data collection, in enrollment sequence. Because AR use was visible, participants and the treating orthodontist could not be blinded to allocation; however, the examiners assessing Plaque Index, Gingival Index, and bracket bond failure, and the data analyst, remained blinded throughout, with the allocation key held separately until the analysis was finalized.

4. Intervention

Both groups received identical standard chairside oral hygiene instruction from the treating orthodontist at appliance placement, covering modified Bass brushing technique, interdental brush use, and fluoride mouth rinse. The AR group additionally received a custom-developed, marker-based smartphone AR application, using the patient's own intraoral photographs and a generic bracket-and-archwire 3D model to display correct toothbrushing angles, interdental brush/floss threading technique, and a simplified animation of anticipated tooth alignment progress at each recall visit; participants were instructed to use it at least three times during the first week and as needed thereafter, with usage logged automatically. The conventional group received a standard



illustrated printed pamphlet covering the same content, without any digital or interactive component.

5. Outcome Measures

The primary outcomes were Plaque Index (PI) and Gingival Index (GI), assessed at six index teeth per participant using the Silness-Löe and Löe-Silness indices by a single calibrated, blinded examiner (intra-examiner kappa = 0.86) at baseline (T0), 6 weeks (T1), 12 weeks (T2), and 24 weeks (T3). Secondary outcomes were: (1) orthodontic care knowledge, assessed with a 20-item multiple-choice questionnaire (range 0–100%) at baseline, immediately post-intervention, and at 24-week retention (validity described in Section 2.7); (2) appointment attendance rate over 24 weeks; (3) bracket bond failure rate, recorded as re-bonding events per 100 patient-months; and (4) dental anxiety, measured using the Modified Child Dental Anxiety Scale-faces version (MCDASf, range 5–25, higher scores indicating greater anxiety) at baseline and 6 weeks (applicability discussed in Section 2.7).

6. AR Application Usability Assessment

Usability and acceptability of the AR application were assessed in the AR group only, using the validated System Usability Scale (SUS, range 0–100) administered at the 6-week follow-up visit, together with a brief structured questionnaire on perceived helpfulness and willingness to continue using the application.

7. Operational Definition of Patient Compliance and Instrument Validity

In this study, ‘patient compliance’ was operationalized as a multi-component construct: (1) oral hygiene behavior (PI, GI); (2) attendance-related adherence (appointment attendance, bracket bond survival); and (3) adherence to appliance-care instructions (orthodontic care knowledge). These components were analyzed separately, as each reflects a conceptually distinct behavioral domain that may respond differently to the AR intervention, given inconsistent use of the term ‘compliance’ in the orthodontic literature.

The knowledge questionnaire was adapted from published patient-education instruments, reviewed for content validity by three orthodontists and one health-education specialist, and revised after pilot testing in 15 adolescent orthodontic patients not included in the main trial (Cronbach’s α = 0.78). The MCDASf is a validated instrument for pediatric and adolescent dental anxiety, though validated predominantly in general dental rather than orthodontic-treatment contexts; this is noted as a limitation in the Discussion.

8. Statistical Analysis

Data were analyzed using SPSS v.26 and R (v.4.3, lme4 and emmeans packages). Continuous variables were tested for normality (Shapiro-Wilk test) and are presented as mean $\pm$ standard deviation. For longitudinal outcomes (PI, GI, orthodontic care knowledge), a linear mixed-effects model was used with group, time, and group $\times$ time interaction as fixed effects, a random intercept for participant, and an unstructured covariance structure, allowing all randomized participants to contribute available data under a missing-at-random assumption. Between-group comparisons at each time point were performed using independent-samples t-tests (or Mann-Whitney U test for

non-normally distributed data) as a secondary, descriptive analysis. Categorical outcomes (appointment attendance, bracket bond failure) were compared using the chi-square test; bracket bond failure was additionally compared using an incidence rate ratio (IRR) with 95% confidence interval from a Poisson model. Effect sizes were calculated alongside p-values: Cohen's d (95% CI) for continuous outcomes, and risk ratio or IRR (95% CI) for categorical and rate outcomes. Statistical significance was set at $p < 0.05$, two-tailed. Analysis followed the intention-to-treat principle, with all 120 randomized participants included in the mixed-model analysis and the descriptive per-time-point comparisons reported for the 116 participants (58 per group) with complete 24-week data.

RESULTS

Of 120 randomized participants (60 per group), 116 completed the 24-week follow-up (AR group $n = 58$, conventional group $n = 58$; overall attrition 3.3%, not significantly different between groups). Baseline characteristics, including age (mean 14.3 ± 1.6 years), sex distribution (52% female), and baseline PI, GI, and knowledge scores, were comparable between groups (all $p > 0.05$), confirming successful randomization.

Table 1. Plaque Index and Gingival Index across time points by study group (mean $\pm$ SD)

Parameter	Group	T0 (Baseline)	T1 (6 wk)	T2 (12 wk)	T3 (24 wk)
Plaque Index (PI) (0–3)	AR education	1.82 ± 0.24	1.21 ± 0.19	0.94 ± 0.17	0.81 ± 0.15
Plaque Index (PI) (0–3)	Conventional	1.79 ± 0.26	1.48 ± 0.22	1.36 ± 0.21	1.42 ± 0.24
Gingival Index (GI) (0–3)	AR education	1.64 ± 0.21	1.08 ± 0.18	0.79 ± 0.15	0.68 ± 0.14
Gingival Index (GI) (0–3)	Conventional	1.61 ± 0.23	1.32 ± 0.20	1.24 ± 0.19	1.31 ± 0.22

Plaque Index (PI) did not differ significantly between groups at baseline (AR 1.82 ± 0.24 vs. conventional 1.79 ± 0.26 , $p = 0.52$), but diverged progressively thereafter, with the AR group showing significantly lower PI at 6 weeks (1.21 ± 0.19 vs. 1.48 ± 0.22 , $p < 0.01$, Cohen's $d = 1.31$, 95% CI 0.91–1.72), 12 weeks (0.94 ± 0.17 vs. 1.36 ± 0.21 , $p < 0.001$, $d = 2.20$, 95% CI 1.74–2.66), and 24 weeks (0.81 ± 0.15 vs. 1.42 ± 0.24 , $p < 0.001$, $d = 3.05$, 95% CI 2.51–3.59) (Table 1, Figure 2); the group $\times$ time interaction from the mixed-effects model was significant ($p < 0.001$), confirming that the rate of change in PI over time differed between groups rather than reflecting a constant offset. Notably, the conventional group showed a rebound increase in PI between 12 and 24 weeks, whereas the AR group maintained a continued downward trend.

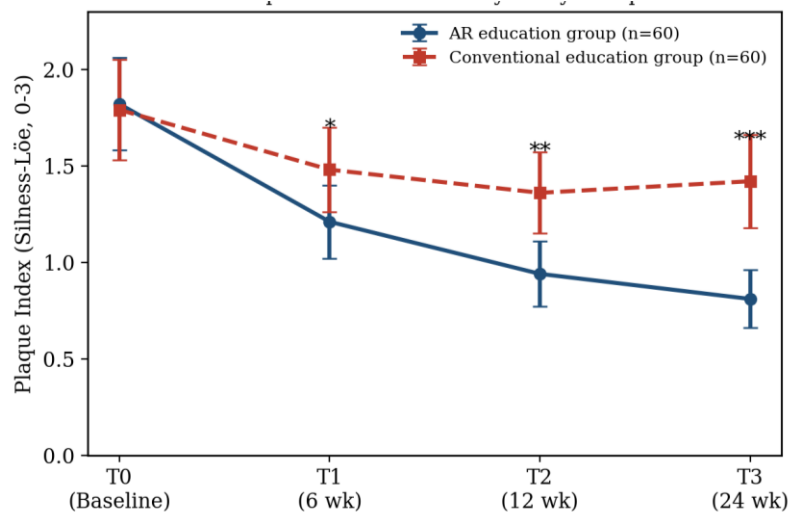


Figure 2. Plaque Index over time by study group. Error bars represent $\pm$ SD. * $p < 0.01$, ** $p < 0.001$, * $p < 0.001$ (independent-samples t-test at each time point).**

Gingival Index (GI) followed a closely parallel pattern (Table 1, Figure 3), with no significant baseline difference (AR 1.64 ± 0.21 vs. conventional 1.61 ± 0.23 , $p = 0.61$) but significantly lower GI in the AR group at 6 weeks (1.08 ± 0.18 vs. 1.32 ± 0.20 , $p < 0.01$, $d = 1.26$, 95% CI 0.86–1.66), 12 weeks (0.79 ± 0.15 vs. 1.24 ± 0.19 , $p < 0.001$, $d = 2.63$, 95% CI 2.13–3.13), and 24 weeks (0.68 ± 0.14 vs. 1.31 ± 0.22 , $p < 0.001$, $d = 3.42$, 95% CI 2.84–3.99), with a significant group $\times$ time interaction ($p < 0.001$) consistent with the PI findings.

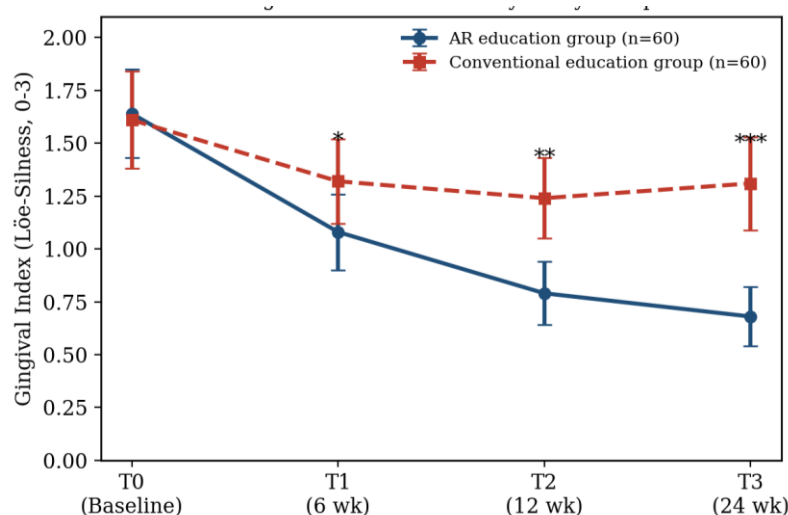


Figure 3. Gingival Index over time by study group. Error bars represent $\pm$ SD.

Orthodontic care knowledge scores were comparable at baseline (AR $51.8 \pm 7.1\%$ vs. conventional $52.6 \pm 7.4\%$, $p = 0.68$). Immediately following the educational intervention, the AR group achieved significantly higher scores than the conventional group ($89.4 \pm 6.2\%$ vs. $68.7 \pm 8.9\%$, $p < 0.001$, $d = 2.70$, 95% CI 2.19–3.20), and this advantage was substantially retained at 24 weeks ($81.2 \pm 7.4\%$ vs. $58.3 \pm 9.6\%$, $p < 0.001$, $d = 2.67$, 95% CI 2.17–3.17), indicating superior knowledge acquisition and retention in the AR group (Table 2, Figure 4); the group $\times$ time interaction was significant ($p < 0.001$).

Table 2. Orthodontic care knowledge scores by study group and time (mean $\pm$ SD, %)

Group	Baseline (T0)	Immediate post-intervention	Retention (24 wk, T3)
AR education (n = 58)	51.8 ± 7.1	89.4 ± 6.2	81.2 ± 7.4
Conventional (n = 58)	52.6 ± 7.4	68.7 ± 8.9	58.3 ± 9.6

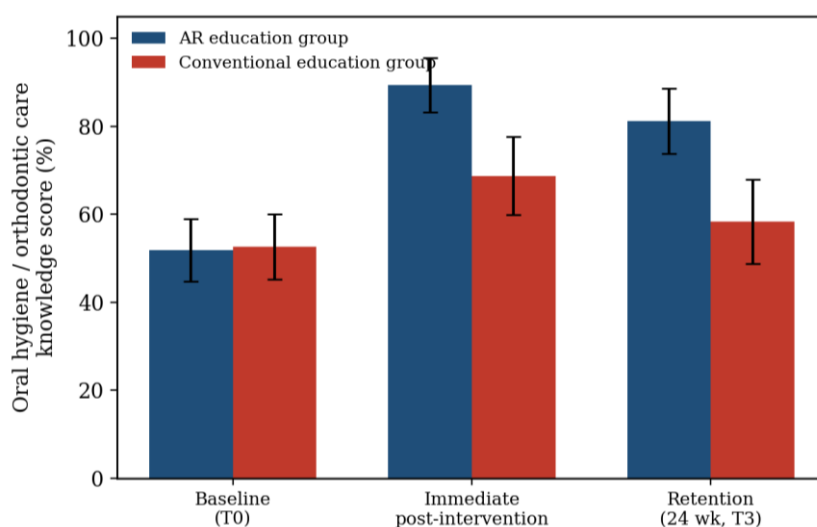


Figure 4. Orthodontic care knowledge score by study group and time. Error bars represent $\pm$ SD.

Appointment attendance over the 24-week observation period was significantly higher in the AR group (96.2%) than in the conventional group (87.4%, χ^2 test, $p < 0.01$; risk ratio 1.10, 95% CI 1.03–1.18, based on total scheduled appointments across the observation period rather than a single per-participant event). Bracket bond failure rate was significantly lower in the AR group (4.8 per 100 patient-months) compared with the conventional group (9.6 per 100 patient-months, $p < 0.01$; incidence rate ratio 0.50, 95% CI 0.27–0.92) (Table 3, Figure 5).

Dental anxiety (MCDASf) did not differ significantly between groups at baseline (AR 14.2 ± 3.1 vs. conventional 14.6 ± 3.3 , $p = 0.58$), but the AR group showed a significantly greater reduction at 6 weeks (10.8 ± 2.6 vs. 13.1 ± 2.9 , $p < 0.001$, $d = 0.84$, 95% CI 0.46–1.21) (Table 3, Figure 5), suggesting



that the interactive visualization of treatment progress and procedures contributed to reduced treatment-related apprehension.

Table 3. Compliance, bracket bond survival, and dental anxiety outcomes by study group

Outcome	AR education group	Conventional group	p-value
Appointment attendance (%)	96.2	87.4	<0.01
Bracket bond failure rate (per 100 patient-months)	4.8	9.6	<0.01
MCDASf anxiety score, baseline (T0)	14.2 ± 3.1	14.6 ± 3.3	0.58
MCDASf anxiety score, 6 weeks (T1)	10.8 ± 2.6	13.1 ± 2.9	<0.001

Among AR group participants, the mean System Usability Scale score was 82.4 ± 7.8 , corresponding to an 'excellent' usability grade and exceeding the commonly cited average SUS benchmark of 68 (Figure 5, panel C). On the structured acceptability questionnaire, 91% of AR group participants reported that the application helped them understand how to clean around their brackets, and 87% indicated willingness to continue using the application for the remainder of their treatment.

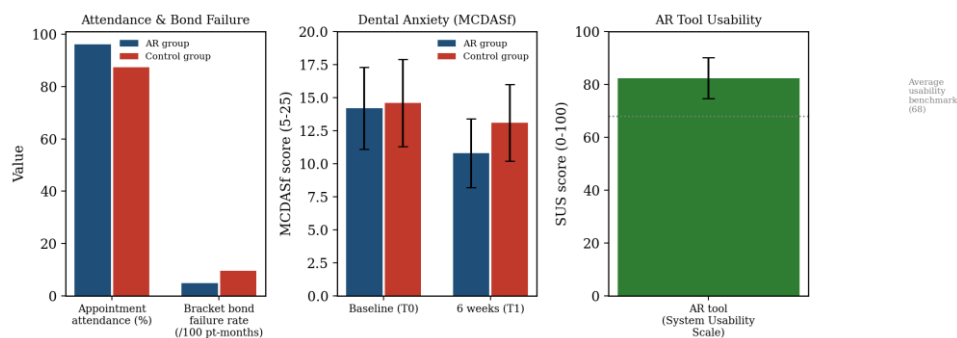


Figure 5. Compliance and usability outcomes: (A) appointment attendance and bracket bond failure rate, (B) dental anxiety (MCDASf) at baseline and 6 weeks, (C) AR application usability (System Usability Scale) in the AR group.

DISCUSSION

This randomized controlled trial demonstrates that a smartphone-based AR educational application, used as an adjunct to standard chairside instruction, produced clinically and statistically significant improvements in oral hygiene status, knowledge acquisition and retention, appointment attendance, bracket bond survival, and dental anxiety among adolescent fixed-appliance orthodontic patients, relative to conventional education alone. These findings extend the existing literature on digital compliance-enhancing interventions in orthodontics, which has predominantly focused on two-dimensional smartphone reminder or gamification applications (Farhadifard et al., 2020; Deleuse et al., 2020), by demonstrating that the added three-dimensional, interactive visualization capability of AR confers a measurable additional benefit.

The progressive divergence in Plaque Index and Gingival Index between groups, together with the rebound in plaque accumulation observed in the conventional group between 12 and 24 weeks, is consistent with previously reported patterns of declining oral hygiene compliance over the course of orthodontic treatment, particularly once the novelty of initial chairside instruction fades (Farhadifard et al., 2020). The sustained improvement observed in the AR group suggests that the interactive, repeatable nature of the AR tool - allowing patients to revisit and re-practice technique visualization outside the clinical setting - may help counteract this typical decline, a mechanism consistent with the rationale proposed for multimedia-reinforced oral hygiene education more broadly.

The superior knowledge retention observed in the AR group aligns with established principles of multimedia and experiential learning, in which three-dimensional, patient-specific, and interactive content is processed and retained more effectively than static or generic instructional material. This is consistent with findings from AR-based dental education among dental students, where AR-guided tooth carving training improved procedural accuracy and learner confidence relative to conventional plastic-model-based instruction (Lim et al., 2023), and with broader reviews identifying enhanced comprehension as a key advantage of AR-based patient communication in dentistry (Fahim et al., 2022; Rosu et al., 2025).

The higher appointment attendance and lower bracket bond failure rate observed in the AR group may reflect both improved technical hygiene skill, reducing gingival inflammation-related discomfort that can discourage attendance, and enhanced patient engagement and motivation fostered by the interactive nature of the AR intervention, including the simulated tooth-movement feedback feature, which may have reinforced patients' perceived progress and investment in treatment continuation. This interpretation is consistent with prior evidence that active, personalized digital engagement strategies - including structured reminders and messaging-based follow-up - can reduce treatment duration and bracket bond failure in orthodontic patients (Al-Abdallah et al., 2021).

The significant reduction in dental anxiety observed in the AR group supports the growing recognition of AR's anxiety-reducing potential in dental patient communication, attributed to its capacity to demystify clinical procedures through clear, patient-controlled visualization rather than passive verbal explanation alone (Fahim et al., 2022). For adolescent patients, who may be particularly sensitive to unfamiliar clinical environments and procedures, this anxiety-reducing effect may carry additional value beyond its direct contribution to compliance, potentially improving the overall treatment experience and long-term attitudes toward dental care.

The excellent System Usability Scale score (82.4) and high patient-reported acceptability observed in this study indicate that the AR application was well received by the adolescent population, a finding consistent with this age group's generally high baseline familiarity and comfort with smartphone-based interactive technology (Shah et al., 2025). This favorable usability profile is an important precondition for real-world clinical adoption, as even a highly effective

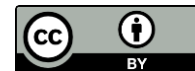


educational tool is unlikely to achieve meaningful impact if patients find it difficult or unappealing to use.

This study has several limitations that constrain the interpretation and generalizability of its findings. First, it was conducted at a single university-affiliated orthodontic clinic; effect sizes for compliance-related outcomes can vary substantially with clinic-specific factors such as baseline patient education practices, staff-to-patient ratios, and socioeconomic and digital-literacy profiles of the patient population, and the large effect sizes observed here (Cohen's d up to 3.4) may not replicate at other centers or in populations with lower smartphone access or digital familiarity; multi-center replication is therefore needed before these results can be generalized. Second, the 24-week observation period, while adequate to capture early- and mid-treatment compliance trends, is substantially shorter than the typical duration of comprehensive fixed orthodontic treatment, which frequently extends to 18–24 months; whether the AR group's advantage in oral hygiene, knowledge retention, and attendance is sustained, attenuated, or lost over this longer horizon—particularly once the novelty of a new digital tool wears off—cannot be determined from the present data and represents an important open question. Third, because the AR application was necessarily visible to participants and the treating orthodontist, this trial could not blind participants or intervention delivery, so a Hawthorne or novelty effect associated with receiving a newly introduced technology, rather than the specific educational content of the AR application itself, cannot be excluded as a contributor to the observed between-group differences; only outcome assessment and data analysis were blinded. Fourth, the marker-based AR application used here is a relatively simple implementation compared with more advanced markerless or intraoral-scan-integrated AR systems now emerging in orthodontic practice (Lo et al., 2021; Sipiyaruk et al., 2023), so these findings should not be assumed to generalize to more sophisticated AR platforms, which may yield different — potentially greater, but also potentially more resource-intensive — effects. Fifth, the orthodontic care knowledge questionnaire had only limited psychometric evaluation (content review and a 15-participant pilot for internal consistency) rather than full validation in an independent adolescent orthodontic sample, and the MCDASf, although a well-validated instrument for dental anxiety generally, has not been specifically validated for the sustained, multi-visit context of fixed orthodontic treatment; both limitations warrant caution in interpreting the magnitude, if not the direction, of the knowledge and anxiety findings. Finally, dental anxiety was assessed only at baseline and 6 weeks, so no conclusions can be drawn about whether the anxiety-reduction benefit persists over the remainder of treatment, and the cost, technical maintenance burden, and scalability of developing and updating patient-specific AR content within routine general orthodontic practice were not evaluated in this trial and require dedicated economic and implementation research (Shah et al., 2025; Rosu et al., 2025).

CONCLUSIONS

This randomized controlled trial demonstrates that a smartphone-based augmented reality educational application, used alongside standard chairside instruction, significantly improved oral hygiene status (Plaque Index and Gingival Index), orthodontic care knowledge acquisition and



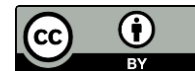
retention, appointment attendance, bracket bond survival, and dental anxiety among adolescent patients undergoing fixed orthodontic treatment, compared with conventional verbal and printed education alone. The AR application achieved excellent perceived usability (System Usability Scale score of 82.4) and high patient acceptability. These findings support augmented reality as a promising, engaging, and well-accepted adjunctive educational tool capable of meaningfully improving adolescent compliance during fixed orthodontic treatment. Given the demonstrated clinical benefits and favorable usability, future research should prioritize longer-term, multi-center validation, exploration of more advanced markerless AR platforms, and assessment of the cost-effectiveness and scalability of integrating AR-based patient education into routine general and specialist orthodontic practice.

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