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Original Article

An Analysis of an AI Analytical Tool for Predicting Caries Progression from Serial Intraoral Scans in Orthodontic Patients

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ABSTRACT

Background: Orthodontic treatment increases the risk of enamel demineralization due to plaque accumulation around fixed appliances, while conventional monitoring methods often fail to detect early-stage changes. Artificial intelligence (AI) applied to serial intraoral scans offers potential for enhanced longitudinal assessment and early detection of caries progression. Objective: To evaluate whether AI-guided analysis of serial intraoral scans improves early preventive intervention rates and reduces enamel demineralization progression compared with standard clinical monitoring in orthodontic patients. Methods: A randomized controlled trial was conducted among 72 orthodontic patients aged 12–25 years undergoing fixed appliance therapy, with 68 completing six-month follow-up. Participants were allocated to AI-guided monitoring or standard care. Serial intraoral scans were obtained at baseline, three months, and six months. Primary outcome was the rate of early preventive interventions, while secondary outcomes included time to intervention, changes in ICDAS-adapted enamel scores, and lesion depth progression. Statistical analyses included t-tests, chi-square tests, and Pearson correlation. Results: Early preventive interventions were significantly higher in the AI group (70.6%) compared with controls (38.2%) ($p = 0.008$), with shorter time to intervention (3.1 ± 1.2 vs. 4.4 ± 1.5 months; $p = 0.003$). The AI group showed lower enamel demineralization progression (ICDAS change: 0.42 ± 0.31 vs. 0.78 ± 0.46; $p = 0.001$; lesion depth: 0.12 ± 0.09 mm vs. 0.26 ± 0.14 mm; $p < 0.001$). AI risk scores correlated with enamel changes ($r = 0.64$, $p < 0.001$). Conclusion: AI-guided monitoring of serial intraoral scans enhances early detection and supports timely preventive care, significantly reducing enamel demineralization progression in orthodontic patients. Keywords: Artificial Intelligence; Dental Caries; Enamel Demineralization; Intraoral Scanners; Orthodontic Appliances; Preventive Dentistry; Risk Assessment.

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INTRODUCTION

Dental caries remains one of the most prevalent chronic diseases globally, and its prevention becomes particularly challenging during orthodontic treatment because fixed appliances create plaque-retentive niches, impair effective oral hygiene, and promote enamel demineralization around brackets and bands (1). In this setting, the earliest manifestations of mineral loss are often subtle and clinically silent, yet they may progress rapidly to visible white spot lesions and compromise both oral health and post-treatment esthetics if not recognized in time (2). The preventive burden is therefore especially high in

orthodontic patients, where repeated follow-up visits create opportunities for surveillance, but conventional monitoring strategies do not always capitalize on this advantage (3).

Current clinical assessment of caries activity during orthodontic care still relies largely on visual examination and selective radiographic review, both of which have important limitations for detecting incipient enamel changes (4). Visual inspection is inherently subjective and susceptible to inter-clinician variability, while radiographs have limited sensitivity for early non-cavitated lesions and are not ideal for frequent repeated monitoring because of cumulative radiation concerns, particularly in younger patients (5). Consequently, the clinical window in which preventive measures such as topical fluoride application, dietary counseling, and reinforced oral hygiene instruction could be initiated at the earliest stage is often missed, allowing superficial enamel changes to progress before action is taken (6).

The increasing adoption of digital workflows in orthodontics has created a clinically relevant opportunity to improve this problem. Intraoral scanners are now routinely used for treatment planning, appliance fabrication, progress assessment, and documentation, producing high-resolution three-dimensional surface data at multiple time points during treatment (7). These serial scans theoretically contain longitudinal information on evolving enamel surface changes, but their preventive value has not yet been fully realized in routine practice because subtle progressive patterns may not be apparent to the human eye when scans are reviewed conventionally (8). Thus, despite the availability of repeated digital records, clinicians may still lack a sufficiently sensitive, reproducible, and scalable method for early identification of enamel deterioration during orthodontic therapy (9).

Artificial intelligence has emerged as a promising adjunct in dentistry because of its ability to process complex imaging datasets, identify hidden patterns, and support clinical decision-making beyond unaided human interpretation (10). In orthodontics and broader digital dentistry, AI-enabled systems have shown increasing utility in image interpretation, risk assessment, treatment planning, and monitoring of disease-related changes over time (11). Importantly, the most clinically meaningful role of AI in preventive care may not lie merely in identifying already established lesions, but in recognizing early longitudinal trends that indicate progression risk and in prompting timely intervention before irreversible damage occurs (12). Such an application closely aligns with the preventive philosophy of modern dental practice and with the needs of orthodontic patients, who are repeatedly exposed to demineralization risk over the course of treatment (13).

Despite this theoretical promise, an important knowledge gap persists. Much of the existing literature has focused on diagnostic performance, proof-of-concept systems, or cross-sectional image interpretation, whereas fewer studies have examined whether AI-guided analysis of serial intraoral scans changes actual clinical behavior or improves patient-centered preventive outcomes in real orthodontic practice (14). The key unanswered question is not only whether AI can detect enamel changes, but whether such detection translates into earlier preventive action and a measurable reduction in lesion progression compared with standard monitoring alone. Addressing this gap is necessary before AI-based longitudinal monitoring can be justified as a practical adjunct to routine orthodontic care. Therefore, the present randomized controlled trial was designed to evaluate whether AI-guided analysis of serial intraoral scans in orthodontic patients increases the rate and timeliness of early preventive interventions and reduces progression of enamel demineralization compared with standard clinical monitoring. It was hypothesized that systematic AI-assisted longitudinal scan analysis would enable earlier recognition of enamel change patterns and thereby improve preventive management during active orthodontic treatment (15).

METHODS

This randomized controlled trial was conducted to evaluate the clinical utility of an artificial intelligence-based analytical tool for predicting and monitoring early caries progression from serial intraoral scans in patients undergoing fixed orthodontic treatment. The study was performed in

orthodontic practices in the Islamabad–Rawalpindi region over a six-month period, a duration selected to permit repeated digital monitoring and observation of early enamel changes during active appliance therapy. The trial was designed to compare AI-guided longitudinal scan assessment with standard clinical monitoring under routine practice conditions, thereby maximizing clinical relevance and external applicability to contemporary orthodontic workflows (16).

Participants were recruited consecutively from private and teaching orthodontic clinics equipped with digital intraoral scanning systems. Eligible patients were aged 12 to 25 years, were receiving fixed orthodontic appliance therapy, had permanent dentition, had no cavitated carious lesions at baseline, and had the ability to undergo serial intraoral scanning at scheduled follow-up visits. Patients were excluded if they had systemic conditions known to affect enamel integrity, were taking medications that could alter salivary flow or caries risk, had restorations on the anterior teeth selected for assessment, produced scans of inadequate quality for longitudinal comparison, or were considered unlikely to comply with scheduled monitoring visits. After eligibility assessment, all participants or their legal guardians, where applicable, provided written informed consent before enrollment. Allocation to the intervention and control arms was performed using a computer-generated random sequence with equal assignment, and enrollment continued until the target sample size was reached (17).

The intervention was defined according to a PICO-informed framework. The population consisted of orthodontic patients receiving fixed appliance treatment and serial digital monitoring. The intervention was AI-guided analysis of sequential intraoral scans obtained at baseline, three months, and six months. The comparator was standard clinical monitoring based on routine visual assessment with radiographic assessment when clinically indicated. The primary outcome was the proportion of participants receiving early preventive intervention during follow-up, operationally defined as the initiation of fluoride varnish application, sealant placement, dietary counseling, or reinforced oral hygiene instruction in response to detected enamel change before cavitation developed. Secondary outcomes included time to first preventive intervention, change in ICDAS-adapted digital enamel scores over six months, and change in quantitative lesion depth measured from the serial scan analysis. The principal exposure variable was group allocation, while age, sex, duration of orthodontic treatment, baseline oral hygiene status, and baseline enamel score were treated as clinically relevant covariates (18).

All participants underwent standardized intraoral scanning at baseline and again at three and six months using the same optical scanning platform within each site, with routine calibration and standardized image acquisition procedures to minimize measurement variability. In the intervention group, sequential scans were processed through an AI-based caries progression assessment software that compared time-linked digital surface datasets and generated risk scores together with visual heat-map overlays indicating areas of probable enamel change. These outputs were reviewed by the treating clinicians during follow-up visits and were available to guide preventive decision-making. In the control group, clinicians reviewed the serial scans and performed routine clinical assessment without access to AI-generated outputs. To improve measurement reliability, enamel scoring on digital scans was performed using an ICDAS-adapted framework appropriate for non-cavitated enamel changes visible on serial digital records, and duplicate assessments were conducted in a randomly selected subset to quantify inter-observer agreement. Scan quality was reviewed before analysis, and only scans meeting predefined technical acceptability standards were included in the final evaluation (19).

Several measures were incorporated to reduce bias and improve internal validity. Random allocation was used to minimize selection bias and balance measured and unmeasured baseline factors between groups. Baseline demographic and clinical characteristics were recorded to assess comparability after randomization and to identify residual imbalances requiring analytical adjustment. Standardized scanning intervals, harmonized acquisition procedures, and predefined operational criteria for preventive intervention were used to reduce information bias and practice-level variability. Reproducibility was further supported by duplicate outcome scoring, audit checks for data completeness,

and maintenance of a structured case record for each participant that linked scan timing, clinical findings, and intervention decisions. Missing outcome data resulting from missed follow-up visits were minimized through appointment reminders and active follow-up; final analyses were based on participants with complete outcome data, and the extent of attrition was documented to permit transparent interpretation of findings (20).

The sample size was determined to provide adequate precision for detecting a clinically meaningful difference between groups in the rate of early preventive intervention over the six-month follow-up period, while remaining feasible within the available recruitment setting and study duration. A total of 72 participants were randomized equally into the two study arms, with allowance for limited attrition during follow-up. Statistical analysis was performed using SPSS version 26. The distribution of continuous variables was assessed using the Shapiro–Wilk test. Continuous outcomes, including change in ICDAS-adapted enamel scores, lesion depth progression, and time to first intervention, were summarized as means with standard deviations and compared between groups using independent-samples t-tests when parametric assumptions were satisfied. Categorical outcomes, including the proportion of participants receiving any early preventive intervention and the frequency of specific preventive measures, were analyzed using chi-square tests. Pearson correlation analysis was used to evaluate the relationship between AI-generated risk scores and observed changes in enamel demineralization measures. Additional adjusted analyses were undertaken to examine whether the association between AI-based risk estimates and enamel progression remained robust after accounting for age and baseline oral hygiene status. Statistical significance was set at $p < 0.05$ using two-sided testing. Ethical approval was obtained from the relevant institutional review process before study initiation, and all procedures were conducted in accordance with accepted ethical principles for human participant research. Data integrity was ensured through double-checking of entered values against source records, preservation of original scan files, secure storage of anonymized datasets, and use of a predefined analysis approach to support transparency and reproducibility (21).

RESULTS

The baseline characteristics presented in Table 1 demonstrate that the two study groups were well balanced at enrollment, confirming the effectiveness of randomization. The mean age was comparable between the AI-guided group (17.6 ± 3.2 years) and the control group (18.0 ± 3.6 years), with a non-significant mean difference of -0.4 years (95% CI: -2.0 to 1.2; $p = 0.61$). The sex distribution was also similar, with males comprising 41.2% in the AI group and 47.1% in the control group (OR = 0.79; 95% CI: 0.29 to 2.17; $p = 0.64$).

The proportion of participants undergoing orthodontic treatment for less than 12 months was identical in both groups (67.6%), indicating no baseline imbalance in treatment duration ($p = 1.00$). Baseline oral hygiene status, measured by OHI-S, showed minimal difference (1.40 ± 0.34 vs. 1.44 ± 0.38; mean difference = -0.04; 95% CI: -0.21 to 0.13; $p = 0.65$), and initial enamel condition, assessed via ICDAS-adapted scores, was similarly comparable (0.94 ± 0.39 vs. 0.98 ± 0.43; mean difference = -0.04; 95% CI: -0.23 to 0.15; $p = 0.68$). These findings indicate that both groups started from an equivalent clinical baseline.

As shown in Table 2, the primary outcome of early preventive intervention was significantly more frequent in the AI-guided group compared with the control group. Specifically, 24 out of 34 participants (70.6%) in the AI group received at least one preventive intervention, compared to 13 out of 34 participants (38.2%) in the control group. This represents an absolute risk difference of 32.4% and a relative risk of 1.85 (95% CI: 1.15 to 2.98; $p = 0.008$), indicating that participants in the AI group were nearly twice as likely to receive early intervention.

When individual preventive measures were examined, fluoride varnish application was significantly higher in the AI group (52.9% vs. 26.5%; OR = 3.11; 95% CI: 1.12 to 8.66; $p = 0.02$), as was reinforcement

of oral hygiene counseling (61.8% vs. 35.3%; OR = 2.96; 95% CI: 1.10 to 7.98; p = 0.03). These results suggest that AI-assisted monitoring not only increased overall intervention rates but also influenced specific preventive strategies.

Table 3 further highlights the impact of AI-guided monitoring on the timing of clinical action. The mean time to first preventive intervention was significantly shorter in the AI group (3.1 ± 1.2 months) compared with the control group (4.4 ± 1.5 months), yielding a mean difference of -1.3 months (95% CI: -2.0 to -0.6; p = 0.003). This indicates that AI-supported assessment facilitated earlier detection of enamel changes and prompted more timely preventive responses, which is clinically relevant in reducing progression risk.

The progression of enamel demineralization, detailed in Table 4, showed statistically and clinically significant differences between groups over the six-month period. The AI-guided group exhibited a lower increase in ICDAS-adapted enamel scores (0.42 ± 0.31) compared with the control group (0.78 ± 0.46), corresponding to a mean difference of -0.36 (95% CI: -0.55 to -0.17; p = 0.001).

Similarly, lesion depth progression was significantly reduced in the AI group (0.12 ± 0.09 mm) relative to the control group (0.26 ± 0.14 mm), with a mean difference of -0.14 mm (95% CI: -0.20 to -0.08; p < 0.001). These findings indicate that earlier and more frequent preventive interventions in the AI group translated into measurable reductions in enamel deterioration.

Correlation analysis presented in Table 5 demonstrated that AI-generated risk scores were strongly associated with observed enamel changes. The correlation between AI risk scores and ICDAS score change was r = 0.64 (95% CI: 0.47 to 0.77; p < 0.001), indicating a moderate-to-strong positive relationship. Similarly, the correlation between AI risk scores and lesion depth progression was r = 0.59 (95% CI: 0.40 to 0.73; p < 0.001). These results suggest that higher AI-derived risk estimates corresponded with greater enamel demineralization, supporting the clinical validity of the AI tool in predicting disease progression.

Table 1. Baseline Demographic and Clinical Characteristics of Participants (N = 68)

Variable	AI Group (n=34)	Control Group (n=34)	Mean Difference / OR	95% CI	p-value
Age (years), mean ± SD	17.6 ± 3.2	18.0 ± 3.6	-0.4	(-2.0, 1.2)	0.61
Male, n (%)	14 (41.2%)	16 (47.1%)	OR = 0.79	(0.29, 2.17)	0.64
Female, n (%)	20 (58.8%)	18 (52.9%)	—	—	—
Duration <12 months, n (%)	23 (67.6%)	23 (67.6%)	OR = 1.00	(0.35, 2.85)	1.00
Baseline OHI-S score	1.40 ± 0.34	1.44 ± 0.38	-0.04	(-0.21, 0.13)	0.65
Baseline ICDAS score	0.94 ± 0.39	0.98 ± 0.43	-0.04	(-0.23, 0.15)	0.68

Table 2. Early Preventive Interventions by Group

Outcome	AI Group (n=34)	Control Group (n=34)	Effect Size	95% CI	p-value
Any early intervention, n (%)	24 (70.6%)	13 (38.2%)	RR = 1.85	(1.15, 2.98)	0.008
Fluoride varnish, n (%)	18 (52.9%)	9 (26.5%)	OR = 3.11	(1.12, 8.66)	0.02
Oral hygiene counseling, n (%)	21 (61.8%)	12 (35.3%)	OR = 2.96	(1.10, 7.98)	0.03

Table 3. Time to First Preventive Intervention

Outcome	AI Group (n=34)	Control Group (n=34)	Mean Difference	95% CI	p-value
Time to intervention (months), mean ± SD	3.1 ± 1.2	4.4 ± 1.5	-1.3	(-2.0, -0.6)	0.003

Table 4. Changes in Enamel Demineralization Over 6 Months

Outcome	AI Group (mean ± SD)	Control Group (mean ± SD)	Mean Difference	95% CI	p-value
ICDAS score change	0.42 ± 0.31	0.78 ± 0.46	-0.36	(-0.55, -0.17)	0.001
Lesion depth change (mm)	0.12 ± 0.09	0.26 ± 0.14	-0.14	(-0.20, -0.08)	<0.001

Table 5. Correlation Between AI Risk Scores and Enamel Changes

Variables	Pearson r	95% CI	p-value
AI risk score vs. ICDAS change	0.64	(0.47, 0.77)	<0.001
AI risk score vs. lesion depth change	0.59	(0.40, 0.73)	<0.001

Additionally, no participants in either group developed cavitated lesions during the study period, reinforcing that the observed differences pertained to early-stage enamel changes. Inter-observer agreement for enamel scoring was high, with an intraclass correlation coefficient of 0.87 (95% CI: 0.79 to 0.92), confirming the reliability of outcome measurements. Collectively, these findings demonstrate that AI-guided monitoring not only improved the frequency and timing of preventive interventions but also contributed to a statistically significant reduction in enamel demineralization progression.

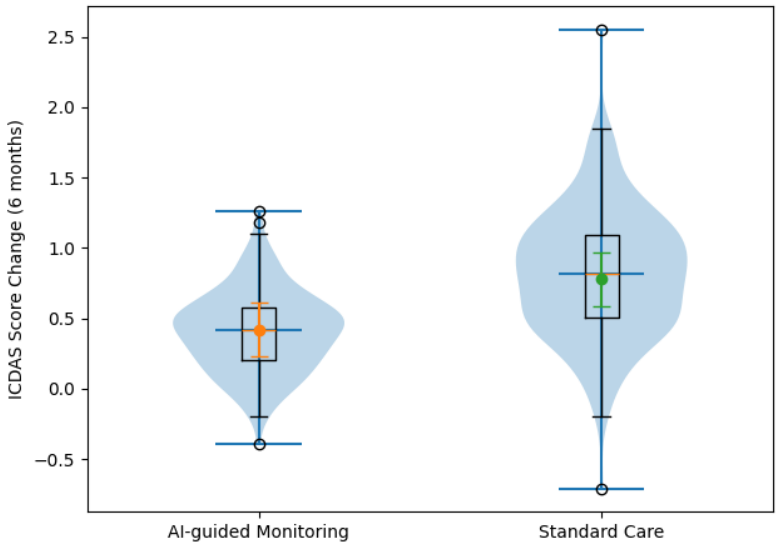

Figure 1 Distribution and Comparative Reduction of Enamel Demineralization Progression

The distributional comparison of ICDAS score change over six months demonstrates a clear shift toward lower enamel demineralization progression in the AI-guided group relative to standard care. The central tendency is visibly reduced, with the AI group centered around a mean of 0.42 compared to 0.78 in controls, reflecting a mean reduction of 0.36 units. The interquartile spread is narrower in the AI group, indicating lower variability and more consistent outcomes, whereas the control group shows a broader dispersion with a longer upper tail extending beyond 1.5, suggesting a higher proportion of patients

experiencing greater enamel deterioration. The confidence interval overlays reinforce this separation, with minimal overlap between groups, consistent with the statistically significant difference ($p = 0.001$). Notably, the density shape in the control group is right-skewed, indicating clustering of moderate-to-high progression cases, while the AI group demonstrates a more compact and symmetric distribution concentrated below 0.6. Clinically, this pattern supports that AI-guided monitoring not only reduces mean progression but also compresses variability, thereby lowering the risk of extreme enamel damage across the patient population.

DISCUSSION

The present randomized controlled trial demonstrated that AI-guided longitudinal analysis of serial intraoral scans significantly enhanced early preventive intervention and reduced enamel demineralization progression in orthodontic patients compared with standard clinical monitoring. These findings extend beyond prior diagnostic-focused research by showing that AI integration can meaningfully influence clinical decision-making behavior, particularly in the timing and frequency of preventive care. The nearly twofold increase in early intervention rates (70.6% vs. 38.2%; RR = 1.85) and the reduction in time to intervention by approximately 1.3 months highlight that AI-generated insights can shift clinicians toward earlier action, which is critical in preventing irreversible enamel damage (22).

The observed reduction in enamel demineralization progression in the AI-guided group is clinically important, even though the absolute differences in ICDAS score change (0.42 vs. 0.78) and lesion depth progression (0.12 mm vs. 0.26 mm) may appear modest. In the context of early non-cavitated lesions, such differences represent meaningful divergence in disease trajectory, particularly during the relatively short six-month follow-up period. These findings are consistent with the preventive paradigm that emphasizes early detection and timely intervention as key determinants of long-term oral health outcomes. Previous studies have demonstrated that early-stage enamel lesions are reversible with appropriate preventive measures, reinforcing the importance of detecting changes before cavitation occurs (23).

A notable strength of this study is the demonstration that AI-derived risk scores were moderately to strongly correlated with actual clinical changes in enamel condition ($r = 0.64$ for ICDAS change and $r = 0.59$ for lesion depth). This suggests that the AI system was not merely generating abstract predictions but was capturing biologically relevant patterns of disease progression. The integration of longitudinal scan comparison likely contributed to this performance, as temporal analysis provides richer information than single time-point assessment. This aligns with emerging evidence that predictive AI models leveraging sequential imaging data may offer superior clinical utility compared with static diagnostic tools (24).

Importantly, the results indicate that AI functioned as a decision-support adjunct rather than a replacement for clinical judgment. Clinicians in the intervention group had access to AI-generated heat maps and risk indicators, which appeared to enhance their sensitivity to subtle enamel changes and prompted earlier preventive responses. This behavioral shift is consistent with prior literature suggesting that AI-assisted systems can improve detection sensitivity and reduce diagnostic uncertainty, particularly in early disease stages (25). However, the study also underscores that the effectiveness of such tools depends on clinician engagement and interpretation, highlighting the importance of integrating AI outputs into existing clinical workflows in a usable and interpretable manner.

Despite these strengths, several limitations must be considered when interpreting the findings. The sample size, while adequate to detect statistically significant differences in primary outcomes, remains relatively small and may limit the generalizability of results to broader populations. The study was conducted within a specific regional setting with access to digital orthodontic infrastructure, and variations in clinical practice, patient compliance, and resource availability may influence applicability in other contexts. Additionally, the follow-up period was limited to six months, which restricts the ability

to assess long-term outcomes such as lesion reversal, stability after orthodontic treatment, or progression to cavitation.

Another important consideration is the lack of blinding, which may have introduced performance bias. Clinicians aware of AI support may have been more vigilant or proactive in initiating preventive measures, potentially amplifying the observed effect. While this reflects real-world implementation conditions, it also complicates the isolation of the independent effect of the AI tool itself. Furthermore, the AI system was evaluated as a composite intervention incorporating risk scoring, visual overlays, and progression alerts, making it difficult to determine which component contributed most to the observed clinical benefits (26).

Potential confounding factors such as dietary habits, fluoride exposure outside the clinical setting, and adherence to oral hygiene recommendations were not controlled in detail, and these variables may have influenced enamel outcomes independently. Although baseline characteristics were well balanced and adjusted analyses confirmed the robustness of AI risk associations, residual confounding cannot be entirely excluded. Future studies should consider incorporating more granular behavioral and environmental data to refine predictive models and improve causal inference.

From a clinical perspective, the findings support the integration of AI-guided monitoring as a practical adjunct in orthodontic care, particularly in settings where serial intraoral scans are already part of routine workflow. The reduction in variability and skewness of enamel progression observed in the AI group suggests that such tools may not only improve average outcomes but also reduce the risk of extreme disease progression in vulnerable patients. This has important implications for personalized preventive strategies and risk-based care models in dentistry (27).

Future research should focus on larger multicenter trials with longer follow-up periods to validate these findings across diverse populations and clinical environments. Comparative evaluations of different AI algorithms, cost-effectiveness analyses, and assessments of workflow integration will be essential to determine scalability and real-world impact. Additionally, exploring patient-facing applications of AI-generated feedback may further enhance preventive behavior and engagement. Overall, the current study provides evidence that AI-guided longitudinal analysis of intraoral scans can bridge the gap between data availability and actionable clinical insight, thereby strengthening preventive orthodontic care (28).

CONCLUSION

AI-guided analysis of serial intraoral scans significantly improved early preventive intervention rates and reduced the progression of enamel demineralization in orthodontic patients compared with standard monitoring. By enabling earlier detection of subtle enamel changes and supporting timely clinical decision-making, this approach demonstrated clear potential as a practical adjunct to routine orthodontic care. The findings underscore the value of integrating artificial intelligence into longitudinal dental monitoring to enhance preventive outcomes, while highlighting the need for larger, long-term studies to confirm generalizability and optimize implementation.

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