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Research Article

AI-Assisted Detection of Secondary Caries and Assessment of Composite Restoration Failure: Association with Periodontal and Oral Biological Factors

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ABSTRACT

Background: Secondary caries and degradation of resin based composite restorations continue to be significant problems for restoration repair and replacement. Besides the material consideration, there are a variety of factors that can affect long-term performance of the composite restorations including periodontal inflammation, plaque accumulation, salivary characteristics, and cariogenic microorganisms. AI supported diagnostic systems could be available to assist in the detection of recurrent caries and the assessment of risk of failure of restorations.

Objective: To evaluate AI-assisted detection of secondary caries and assess composite restoration failure in relation to periodontal, oral biological, and restoration-related factors.

Methods: This analytical cross-sectional study included 85 participants, with one eligible composite restoration evaluated per participant, resulting in 85 restorations for analysis. Clinical, periodontal, radiographic, salivary, and microbiological parameters were recorded. Secondary caries was assessed using combined clinical and radiographic examination, while AI-assisted radiographic assessment was performed using Diagnocat™ for detection of secondary caries. Composite restoration failure was determined clinically using predefined criteria. Plaque Index, Gingival Index, bleeding on probing, probing pocket depth, salivary pH, salivary flow rate, buffering capacity, Streptococcus mutans level, restoration age, number of restored surfaces, and marginal adaptation were evaluated. Diagnostic performance measures and multivariable logistic regression were used for statistical analysis.

Results: Secondary caries was confirmed in 29 of 85 restorations (34.1%), while 25 restorations (29.4%) were clinically classified as failed. AI-assisted secondary caries detection demonstrated a sensitivity of 89.7%, specificity of 91.1%, positive predictive value of 83.9%, negative predictive value of 94.4%, and overall accuracy of 90.6%. Restorations with secondary caries were associated with significantly higher Plaque Index, Gingival Index, and probing pocket depth, along with lower salivary pH and flow rate. High S. mutans levels were also significantly more frequent in restorations affected by secondary caries. Composite restoration failure was significantly associated with secondary caries, restoration age >5 years, involvement of three or more surfaces, poor marginal adaptation, poor oral hygiene, and high S. mutans levels. In multivariable analysis, secondary caries, poor marginal adaptation, restoration age >5 years, and high S. mutans levels remained independently associated with composite restoration failure.

Conclusion: AI-assisted radiographic assessment demonstrated high diagnostic performance for secondary caries detection. Composite restoration failure was independently associated with secondary caries, defective marginal adaptation, greater restoration age, and elevated S. mutans levels. These findings support the use of AI as an adjunct to conventional secondary caries detection while emphasizing the importance of periodontal, biological, and restoration-related factors in the clinical assessment of composite restoration outcomes.

Keywords: Artificial Intelligence, Secondary Caries, Composite Restoration, Restoration Failure, Periodontal Health, Salivary Ph, Streptococcus Mutans, Oral Biofilm.

INTRODUCTION

Resin-based composite materials have become an important component of contemporary restorative dentistry because of their favorable esthetics, conservative tooth preparation requirements, adhesive properties, and ability to reproduce natural tooth appearance. The Mechanical performance and clinical longevity have improved due to improvements in resin matrices, the use of fillers, bonding systems, and polymerization techniques. However, with all these developments, composite restorations can fail overtime as a result of mechanical loading, stresses caused due to polymerization, hydrolytic degradation, marginal breakdown, buildup of biofilm, and recurring carious activity. This means replacement or repair of defective composite restorations still provide a significant percentage of routine restorative dental care (1-3).

Secondary caries or recurrent caries is the caries that forms around or under a restoration and is one of the most significant causes for replacement of resin-based composite restorations. Diagnosis can be difficult due to the possibility that early lesions may appear as marginal staining, minor gaps, radiographic artifacts or non-cavitated demineralization. Typical diagnosis will involve a clinical examination and palpation, and typically supplemented by bitewing or periapical radiographs. But, small lesions at proximal or cervical margins can only be detected when a great deal of minerals have been lost. However, excessive interpretation of the margins that are not clinically discolored or radiographically altered can result in removal and replacement of presumably adequate restorations (4-6).

In dentistry, the progress of artificial intelligence and machine-learning applications has opened the door for computer-assisted interpretation of dental images. Diagnostic systems using artificial intelligence can interpret the pattern of radiographic and clinical images, and can help the clinician identify carious lesions and marginal defects, as well as other structural defects. These types of systems can be used to enhance the consistency of diagnostic procedures and to ensure the timely identification of lesions that may not be noticed by routine examination. In restorative dentistry, AI-assisted assessment might be able to go further than just identifying lesions and add in the attributes of the restoration and factors relating to the patient in order to predict the likelihood of a future restoration failure (7-9).

The clinical performance of a composite restoration depends on more than its mechanical and material properties. The condition of the periodontium around the restored tooth can play a significant role in the longevity of the restored tooth. Local biofilm buildup and gingivitis can be caused by plaque retentive restoration margins, poor proximal contours, gingival overhangs, or surface roughness. Over time, plaque may build up around the edges of the restoration leading to an increase in acid production and adjacent tooth structure demineralization. Probing for bleeding, pocket depth, and plaque control could therefore be indicators of a plaque environment where recurrent caries and loss of the restoration are more likely to occur (10).

The oral biological factors are also important in the initiation and progression of carious lesions. Saliva performs mechanical clearance, buffering of acids, mineral exchange and antimicrobial function in the oral homeostasis. Xerostomia and decreased buffering capacity may delay the neutralisation of the acids after carbohydrate ingestion, and may affect remineralisation. Likewise, a pH of the saliva favoring the growth and metabolism of cariogenic microorganisms. Streptococcus mutans has long been linked to adhesion to tooth surfaces, acid production and biofilm formation, and therefore, high levels of this bacteria may be a good indicator of caries susceptibility (11, 12).

The interaction between restoration-related, periodontal, and biological factors is particularly relevant in patients with existing composite restorations. A restoration that has a small amount of deterioration can provide an ecological niche for the growth of plaque and cariogenic microorganisms. If this happens in a poor oral hygiene patient, a diminished salivary protection or increased cariogenic bacteria, the risk of reoccurrence of caries and subsequent restoration failure may rise. Thus, an assessment of restoration integrity alone, without an evaluation of the surrounding periodontal and biological environment, may be incomplete in assessing the long-term prognosis for the restoration (13).

AI-assisted systems may offer an opportunity to integrate several of these risk dimensions into a more comprehensive evaluation. Rather than relying solely on visible defects, computer-assisted analysis could potentially combine image-based findings with restoration age, marginal adaptation, periodontal status, plaque accumulation, and oral biological factors. Such an approach may help distinguish restorations that are currently acceptable from those at increased risk of deterioration. Earlier identification of high-risk restorations could support preventive intervention, targeted oral hygiene measures, repair of localized defects, and closer clinical surveillance before extensive failure develops (14).

The use of AI to diagnose secondary caries and predict failure of composite restorations is still relatively under-researched, and the combined effect of periodontal and oral biological factors has not been well studied. A number of studies are reported in the literature that included mostly radiographic caries detection and did not consider the synergistic effects of periodontal health, salivary parameters, microbial parameters, and restoration-related parameters. Clinical trials are thus needed that explore these variables simultaneously and consider the value-added potential of AI-assisted assessment in identifying at-risk restorations.

The present study was undertaken to evaluate AI-assisted detection of secondary caries and the clinical assessment of composite restoration failure in relation to periodontal, oral biological, and restoration-related factors**.** Specifically, the study examined the associations of plaque accumulation, gingival inflammation, probing pocket depth, salivary pH, salivary flow rate, buffering capacity, Streptococcus mutans levels, restoration age, number of restored surfaces, and marginal adaptation with secondary caries and composite restoration failure. In addition, the diagnostic performance of AI-assisted radiographic assessment for secondary caries detection was compared with the predefined clinical-radiographic reference assessment. Because of the cross-sectional design, the study focused on detection, classification, and associated factors rather than prediction of future restoration failure.

METHODOLOGY

This analytical cross-sectional study was conducted at Women Medical and Dental College Abbottabad from January 2025 to June 2025. The study was designed to evaluate the diagnostic performance of AI-assisted assessment for the detection of secondary caries and to determine the periodontal, oral biological, and restoration-related factors associated with composite restoration failure. Because the study was cross-sectional, restoration failure was assessed at the time of examination rather than prospectively predicted.

Ethical approval for the study was obtained from the Institutional Review Board/Ethical Review Committee**.** Written informed consent was obtained from all participants before enrolment. The study was conducted in accordance with applicable institutional ethical standards and the principles of the Declaration of Helsinki.

A total of 85 participants with existing direct composite restorations were included in the study. Only one eligible composite restoration was included from each participant. When more than one eligible composite restoration was present, one restoration was selected using simple random selection and only that restoration was included in the analysis. Thus, the final analytical sample consisted of 85 participants and 85 restorations. Participants were recruited consecutively from eligible patients attending the outpatient dental clinics during the study period.

Patients were eligible if they were aged 18 years or older, of either sex, and had at least one permanent tooth restored with a direct resin-based composite restoration. The restoration had to be sufficiently established to allow clinical evaluation of marginal integrity and possible secondary caries. Participants were required to consent to clinical, periodontal, radiographic, and salivary assessment. Teeth with temporary restorations, primary teeth, recently placed composite restorations, extensive restorations that could not be adequately evaluated, acute periapical infection, or inadequate clinical or radiographic visualization were excluded. Patients with conditions or treatments likely to substantially affect salivary secretion or periodontal status were also excluded where applicable.

After enrolment, demographic and clinical information was recorded using a structured data-collection proforma. Recorded variables included age, sex, oral hygiene practices, smoking status where applicable, frequency of dental visits, tooth type, dental arch, number of restored surfaces, estimated restoration age, and history of previous restoration repair. Each selected composite restoration was examined under adequate illumination after removal of plaque and debris and appropriate drying. Clinical evaluation included marginal adaptation, marginal staining, surface roughness, wear, fracture, chipping, partial loss of restorative material, and evidence of recurrent or secondary caries. Restorations were also categorized according to anatomical location and the number of surfaces involved.

Secondary caries was assessed using clinical examination supplemented by radiographic evaluation when indicated. Particular attention was given to lesions located adjacent to or beneath the margins of existing composite restorations. Suspected lesions were categorized as occlusal, proximal, or cervical/gingival and, where possible, according to enamel or dentinal involvement. The final reference diagnosis of secondary caries was based on the combined clinical and radiographic assessment and was established independently of the AI output.

For AI-assisted evaluation, digital bitewing and/or periapical radiographic images were analyzed using Diagnocat™, an artificial intelligence-based dental diagnostic system developed by Diagnocat Inc., San Francisco, CA, USA. The system uses deep-learning-based image analysis to assist in the identification of carious lesions on dental radiographs. Each selected restoration was assessed for radiographic features suggestive of secondary caries adjacent to the restoration margin. For analysis, the AI output was recorded as positive or negative for secondary caries and was compared with the predefined clinical-radiographic reference assessment. AI results were recorded independently from the reference assessment to minimize interpretation bias. Sensitivity, specificity, positive predictive value, negative predictive value, and overall diagnostic accuracy were calculated for AI-assisted secondary caries detection.

The AI system was not used to prospectively predict subsequent composite restoration failure. Composite restoration status was assessed clinically at the time of examination using predefined criteria.

The periodontal tissues adjacent to the evaluated restoration were examined using standardized periodontal parameters. Plaque Index, Gingival Index, bleeding on probing, probing pocket depth, gingival recession, and overall periodontal status were recorded. Probing pocket depth was measured in millimeters using a calibrated periodontal probe, and periodontal pockets were defined as probing depths of ≥4 mm.

Oral biological parameters were also evaluated. Unstimulated saliva was collected under standardized conditions, preferably before clinical procedures and following an appropriate period without food, drinks, tobacco, toothpaste, or mouthwash. Salivary flow rate was expressed in mL/min, and salivary pH was measured using a calibrated pH measurement method. Salivary buffering capacity was assessed using the laboratory or commercial test available in the department. Microbiological evaluation focused on Streptococcus mutans, which was categorized as low/moderate or high according to the laboratory protocol. Oral hygiene status and overall caries-risk category were also recorded.

The primary restorative outcome was composite restoration failure. A restoration was considered failed if one or more clinically unacceptable conditions requiring repair or replacement were present, including secondary caries, major marginal breakdown, restoration fracture, partial loss of restorative material, or another defect compromising restoration function or integrity. Restorations without these findings were categorized as clinically successful. The following factors were evaluated for their association with composite restoration failure: restoration age, number of restored surfaces, marginal adaptation, secondary caries, periodontal findings, salivary characteristics, bacterial load, and oral hygiene status.

To maintain consistency, the same predefined clinical criteria were applied throughout data collection. Where more than one examiner participated, examiners were oriented to the study definitions and measurement procedures before data collection. Standard infection-control procedures were followed during oral examination, periodontal probing, radiography, and saliva collection. Each participant was assigned a study identification number, and identifiable information was kept separate from the analytical dataset.

Data were entered and analyzed using IBM SPSS Statistics. Continuous variables, including age, restoration age, Plaque Index, Gingival Index, probing depth, salivary pH, and salivary flow rate, were summarized as mean ± standard deviation for approximately normally distributed data and median with interquartile range where appropriate. Categorical variables were presented as frequencies and percentages. Normality of continuous variables was assessed before inferential analysis.

Independent-samples t-tests were used to compare normally distributed continuous variables between restorations with and without secondary caries and between clinically successful and failed restorations. Mann–Whitney U tests were used for non-normally distributed continuous variables. Categorical variables were compared using the chi-square test or Fisher's exact test where expected cell counts were small.

Univariable analyses were first performed to identify factors associated with composite restoration failure. Clinically relevant variables and variables showing an appropriate association in preliminary analysis were entered into a multivariable binary logistic regression model. Adjusted odds ratios with 95% confidence intervals were reported to identify factors independently associated with restoration failure. A p-value <0.05 was considered statistically significant. For the AI-assisted secondary caries analysis, a 2 × 2 contingency table was constructed against the clinical-radiographic reference diagnosis. Sensitivity, specificity, positive predictive value, negative predictive value, and overall accuracy were calculated.

RESULTS

A total of 85 participants were included, with one composite restoration evaluated per participant, resulting in 85 restorations in the final analysis**.** The mean age of participants was 36.8 ± 10.4 years, with an age range of 18–60 years. Females constituted 47 (55.3%) participants, while 38 (44.7%) were males. Most evaluated restorations were located in posterior teeth, including 44 (51.8%) molars and 29 (34.1%) premolars. The mean age of the composite restorations was 4.6 ± 2.3 years.

Table 1. Demographic and restoration characteristics of participants (n = 85)

Variable	Frequency (%) / Mean ± SD
Age, years	36.8 ± 10.4
Male	38 (44.7%)
Female	47 (55.3%)
Anterior teeth	12 (14.1%)
Premolars	29 (34.1%)
Molars	44 (51.8%)
Maxillary restorations	39 (45.9%)
Mandibular restorations	46 (54.1%)
Restoration age, years	4.6 ± 2.3
One-surface restoration	25 (29.4%)
Two-surface restoration	38 (44.7%)
Three or more surfaces	22 (25.9%)
Previous restoration repair	16 (18.8%)

Overall, 29 of 85 restorations (34.1%) were diagnosed with secondary caries according to the final clinical-radiographic reference assessment. AI-assisted evaluation classified 31 restorations (36.5%) as positive for secondary caries, while conventional clinical examination identified secondary caries in 26 restorations (30.6%). Secondary caries most frequently involved gingival/cervical margins, followed by proximal and occlusal sites.

Table 2. Pattern of secondary caries and AI-assisted detection

Variable	n (%)
Secondary caries confirmed	29 (34.1%)
No secondary caries	56 (65.9%)
AI-positive for secondary caries	31 (36.5%)
AI-negative	54 (63.5%)
Clinically detected secondary caries	26 (30.6%)
Gingival/cervical lesion	13 (44.8%)*
Proximal lesion	10 (34.5%)*
Occlusal lesion	6 (20.7%)*
Enamel-limited lesion	9 (31.0%)*
Dentin involvement	20 (69.0%)*

*Percentages calculated among the 29 restorations with confirmed secondary caries.

The AI-assisted assessment correctly identified 26 of 29 restorations with secondary caries and correctly classified 51 of 56 restorations without secondary caries. This corresponded to a sensitivity of 89.7%, specificity of 91.1%, positive predictive value of 83.9%, negative predictive value of 94.4%, and overall diagnostic accuracy of 90.6%.

Table 3. Diagnostic performance of AI-assisted secondary caries detection

AI-assisted result	Secondary caries present	Secondary caries absent	Total
Positive	26	5	31
Negative	3	51	54
Total	29	56	85

Diagnostic parameter	Value
Sensitivity	89.7%
Specificity	91.1%
Positive predictive value	83.9%
Negative predictive value	94.4%
Accuracy	90.6%

Periodontal parameters differed significantly according to secondary caries status. Participants with secondary caries had significantly higher mean Plaque Index scores (1.78 ± 0.54 vs. 1.21 ± 0.48; $p < 0.001$), Gingival Index scores (1.52 ± 0.49 vs. 1.08 ± 0.43; $p < 0.001$), and probing pocket depth (3.42 ± 0.71 vs. 2.76 ± 0.63 mm; $p < 0.001$). Bleeding on probing was observed in 18 (62.1%) restorations with secondary caries compared with 16 (28.6%) without secondary caries ($p = 0.003$).

Table 4. Periodontal factors according to secondary caries status

Periodontal variable	Secondary caries, n = 29	No secondary caries, n = 56	p-value
Plaque Index	1.78 ± 0.54	1.21 ± 0.48	<0.001
Gingival Index	1.52 ± 0.49	1.08 ± 0.43	<0.001
Probing pocket depth, mm	3.42 ± 0.71	2.76 ± 0.63	<0.001
Bleeding on probing	18 (62.1%)	16 (28.6%)	0.003
Periodontal pocket ≥4 mm	12 (41.4%)	9 (16.1%)	0.010
Gingival recession	10 (34.5%)	9 (16.1%)	0.052

The mean salivary pH was significantly lower among restorations with secondary caries than among those without secondary caries (6.31 ± 0.39 vs. 6.72 ± 0.36; $p < 0.001$). Salivary flow rate was also significantly lower in the secondary caries group (0.72 ± 0.21 vs. 0.93 ± 0.24 mL/min; $p < 0.001$). High S. mutans levels were detected in 19 (65.5%) participants with secondary caries compared with 15 (26.8%) without secondary caries ($p = 0.001$).

Table 5. Oral biological factors according to secondary caries status

Oral biological factor	Secondary caries, n = 29	No secondary caries, n = 56	p-value
Salivary pH	6.31 ± 0.39	6.72 ± 0.36	<0.001
Salivary flow rate, mL/min	0.72 ± 0.21	0.93 ± 0.24	<0.001
High S. mutans level	19 (65.5%)	15 (26.8%)	0.001
Reduced buffering capacity	17 (58.6%)	15 (26.8%)	0.004
Poor oral hygiene	18 (62.1%)	17 (30.4%)	0.005
High caries-risk category	20 (69.0%)	17 (30.4%)	0.001

Twenty-five of the 85 composite restorations (29.4%) were clinically classified as failed, whereas 60 (70.6%) were clinically successful. The most frequently recorded reason for failure was secondary caries, followed by major marginal breakdown, restoration fracture, and partial or complete restoration loss.

Table 6. Composite restoration outcomes and causes of failure

Outcome	n (%)
Successful restoration	60 (70.6%)
Failed restoration	25 (29.4%)
Secondary caries-related failure	12 (48.0%)*
Major marginal breakdown	6 (24.0%)*
Restoration fracture	4 (16.0%)*
Partial/complete restoration loss	3 (12.0%)*

*Percentages calculated among the 25 failed restorations.

Composite restoration failure was significantly associated with several restoration-related and biological factors. Restorations older than five years had a higher proportion of failure than restorations aged five years or less (47.1% vs. 17.6%; $p = 0.004$). Failure was also more frequent among restorations involving three or more surfaces than among one- or two-surface restorations (50.0% vs. 22.2%; $p = 0.014$). Poor marginal adaptation showed a strong association with failure (58.3% vs. 18.0%; $p < 0.001$).

Table 7. Factors associated with composite restoration failure

Factor	Restoration failure	Restoration success	p-value
Restoration age >5 years	16/34 (47.1%)	18/34 (52.9%)	0.004
Restoration age ≤5 years	9/51 (17.6%)	42/51 (82.4%)	
≥3 restored surfaces	11/22 (50.0%)	11/22 (50.0%)	0.014
1–2 restored surfaces	14/63 (22.2%)	49/63 (77.8%)	
Poor marginal adaptation	14/24 (58.3%)	10/24 (41.7%)	<0.001
Acceptable marginal adaptation	11/61 (18.0%)	50/61 (82.0%)	
Secondary caries present	17/29 (58.6%)	12/29 (41.4%)	<0.001
Secondary caries absent	8/56 (14.3%)	48/56 (85.7%)	
High S. mutans level	16/34 (47.1%)	18/34 (52.9%)	0.004
Low/moderate S. mutans level	9/51 (17.6%)	42/51 (82.4%)	
Poor oral hygiene	16/35 (45.7%)	19/35 (54.3%)	0.005
Good/fair oral hygiene	9/50 (18.0%)	41/50 (82.0%)	

Multivariable logistic regression was performed to identify factors independently associated with composite restoration failure. Secondary caries, poor marginal adaptation, restoration age >5 years, and high **S. mutans** levels remained independently associated with composite restoration failure after adjustment for the other variables included in the model.

Table 8. Multivariable logistic regression analysis of factors independently associated with composite restoration failure

Factor	Adjusted OR	95% CI	p-value
Secondary caries present	4.12	1.42–11.96	0.009
Poor marginal adaptation	3.67	1.25–10.77	0.018
Restoration age >5 years	2.91	1.05–8.06	0.040
High S. mutans level	2.84	1.01–7.96	0.048
High Plaque Index	2.21	0.82–5.96	0.116
Reduced salivary flow	1.88	0.68–5.19	0.223

Because the AI system was used for secondary caries detection rather than prospective prediction of restoration failure, AI diagnostic performance for restoration failure was not reported separately. Composite restoration failure was determined using predefined clinical criteria, and factors associated with failure were evaluated using bivariate analyses and multivariable logistic regression.

Overall, secondary caries and composite restoration failure were more frequent in participants with unfavorable periodontal conditions and cariogenic oral biological profiles. Higher plaque accumulation, gingival inflammation, reduced salivary pH and flow, increased S. mutans levels, older restorations, and defective marginal adaptation were associated with poorer restorative outcomes**.** AI-assisted assessment demonstrated high diagnostic performance for secondary caries detection, while composite restoration failure was assessed clinically and analyzed in relation to associated periodontal, biological, and restoration-related factors.

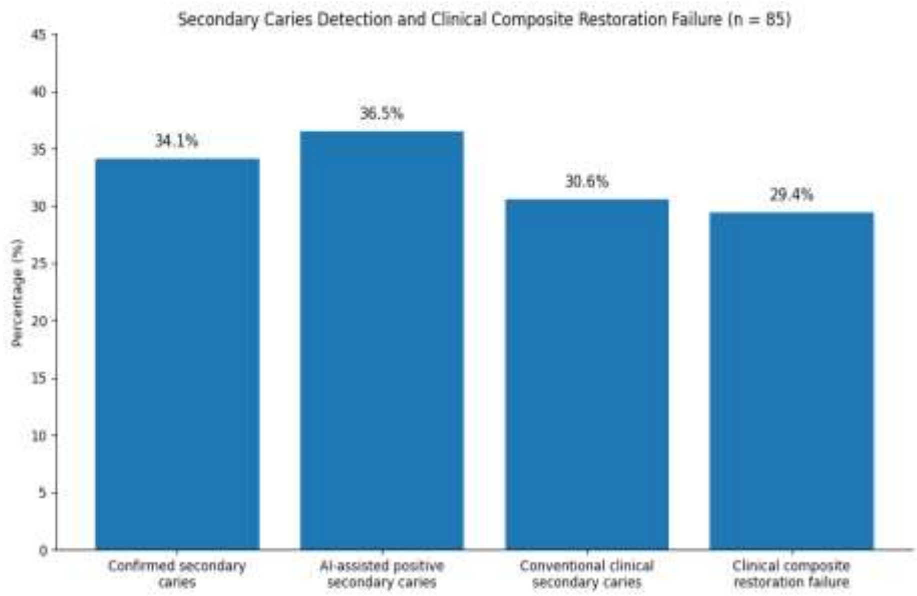

Figure 1. Secondary caries detection and clinical composite restoration failure among study participants (n = 85).

The figure compares confirmed secondary caries (34.1%), AI-assisted positive secondary caries detection (36.5%), conventional clinical secondary caries detection (30.6%), and clinically assessed composite restoration failure (29.4%).

DISCUSSION

The present study evaluated AI-assisted detection of secondary caries together with the clinical assessment of composite restoration failure and its association with periodontal, oral biological, and restoration-related factors. Secondary caries was confirmed in 34.1% of the evaluated restorations, while 29.4% were clinically classified as failed. These findings indicate that recurrent caries and deterioration of restoration integrity remain important clinical problems in teeth restored with resin-based composite materials. The results also support the concept that restoration outcomes are influenced by a combination of restoration characteristics and the surrounding oral environment rather than by material-related factors alone. (15).

AI-assisted radiographic assessment demonstrated a sensitivity of 89.7%, specificity of 91.1%, positive predictive value of 83.9%, negative predictive value of 94.4%, and overall accuracy of 90.6% for secondary caries detection. These findings suggest that AI-assisted image interpretation may be a useful adjunct to conventional clinical and radiographic examination, particularly in identifying subtle radiographic changes adjacent to restoration margins. The high negative predictive value indicates good performance in identifying restorations without secondary caries. However, AI-assisted assessment should complement rather than replace clinical judgement, because the final diagnosis of secondary caries also depends on restoration characteristics, clinical examination, and radiographic interpretation. (16, 17).

Periodontal parameters differed significantly according to secondary caries status. Participants with secondary caries had higher Plaque Index and Gingival Index scores and greater probing pocket depth than those without secondary caries. Bleeding on probing and periodontal pockets of 4 mm or greater were also more frequent in affected restorations. These findings indicate that plaque accumulation and gingival inflammation around restored teeth may contribute to an oral environment that favors bacterial persistence and demineralization adjacent to restoration margins. Defective contours, inadequate marginal adaptation, and plaque-retentive surfaces may further increase the accumulation of cariogenic biofilm, particularly in proximal and cervical regions that are more difficult to clean. (18, 19).

Oral biological factors were also significantly associated with secondary caries. Lower salivary pH and reduced salivary flow were observed among participants with secondary caries, while high Streptococcus mutans levels, reduced buffering capacity, poor oral hygiene, and a high caries-risk profile were more frequent in this group. Saliva plays an important role in oral homeostasis through mechanical cleansing, buffering of acids, antimicrobial activity, and remineralization. Therefore, reduced salivary protection may prolong acidic conditions around restoration margins and facilitate recurrent caries. Similarly, increased levels of cariogenic microorganisms may promote biofilm development and acid production at marginal defects (19).

Several restoration-related factors were significantly associated with composite restoration failure. Restorations older than five years had a greater proportion of failure than newer restorations, while restorations involving three or more surfaces also showed a higher failure rate. Poor marginal adaptation demonstrated one of the strongest associations with failure. In multivariable analysis, secondary caries, poor marginal adaptation, restoration age greater than five years, and high S. mutans levels remained independently associated with composite restoration failure. These findings emphasize that restoration longevity depends on both technical factors and patient-related biological conditions. Regular assessment of restoration margins, oral hygiene, periodontal health, and cariogenic risk may therefore be important in identifying restorations that require closer clinical attention. (20)(14)(12).

The findings of this study have practical relevance because they support a more comprehensive approach to the evaluation of composite restorations. AI-assisted radiographic assessment may improve secondary caries detection, while periodontal examination, salivary assessment, microbial risk evaluation, and careful inspection of restoration integrity provide additional clinical information regarding restoration status. Nevertheless, several limitations should be considered. The study was conducted at a single center and included a relatively small sample of 85 participants, which may limit generalizability. In addition, the cross-sectional design allowed identification of associations but did not establish temporal or causal relationships and did not permit prediction of future restoration failure. The performance of AI-assisted assessment may also vary according to image quality, radiographic technique, and the characteristics of the software used. Larger prospective multicenter studies with longitudinal follow-up are required to determine whether AI-assisted assessment can contribute to the prediction of future restoration deterioration and failure.

CONCLUSION

Secondary caries and composite restoration failure were relatively common among the evaluated restorations and were significantly associated with unfavorable periodontal, biological, and restoration-related characteristics. Higher plaque accumulation, gingival inflammation, deeper probing pocket depth, reduced salivary pH and flow, elevated Streptococcus mutans levels, greater restoration age, multiple restored surfaces, and poor marginal adaptation were associated with poorer restorative outcomes. Secondary caries, poor marginal adaptation, restoration age greater than five years, and high S. mutans levels remained independently associated with composite restoration failure.

AI-assisted radiographic assessment demonstrated high sensitivity, specificity, and overall accuracy for the detection of secondary caries and may serve as a useful adjunct to conventional clinical and radiographic examination. However, composite restoration failure in the present cross-sectional study was assessed clinically rather than prospectively predicted by AI. Integration of AI-assisted caries detection with periodontal evaluation, assessment of salivary and microbial factors, and regular monitoring of restoration margins may support earlier identification of clinically compromised restorations and more individualized preventive and restorative care. Prospective longitudinal studies are required to determine the ability of AI-based systems to predict future restoration failure.

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