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A validation of 3D imaging for non-invasive, tech-assisted diagnosis of caries and erosive tooth wear in primary teeth - an in vitro study

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ABSTRACT

This in vitro study set out to assess the agreement of 3D-colored digital dental images in detecting occlusal caries and erosive tooth wear (ETW) in primary teeth, by comparing indirect digital assessments with conventional direct visual examinations. Extracted primary molars with varying degrees of caries severity and ETW were mounted on modeling wax, with the crowns exposed for the assessments. Then, two independent experiments were conducted. The first analyzed occlusal caries in 233 extracted primary molars using the International Caries Detection and Assessment System (ICDAS, scores 0-6), while the second evaluated ETW in 164 primary molars using the Basic Erosive Wear Examination (BEWE, scores 0-3). Direct visual examinations were performed under standardized lighting, dryness and magnification. For the indirect assessment, teeth were scanned using an intraoral scanner (TRIOS 4, 3Shape), and digital images were assessed via 3Shape Unite software. Agreement between methods was determined using kappa statistics and percent agreement. Substantial agreement was found for caries detection (Kappa=0.64; 71% agreement) with the highest concordance at ICDAS scores 4-6 (>90%) and the lowest at score 0 (36%). For ETW, substantial agreement was also observed Kappa = 0.58; 80% agreement), with highest concordance at BEWE score 2 (99%). The digital method tended to overestimate scores 0 and 1 and underestimate scores 2 and 3 in caries detection. 3D-colored digital images demonstrated substantial agreement with conventional visual methods for detecting both dental caries and ETW in primary teeth. These results highlight its promise as a practical and non-invasive adjunct in pediatric dental diagnostics, with potential to enhance early detection and support the integration of digital tools into routine and remote oral health care.

Key Words: Primary teeth, digital dentistry, 3D image, caries detection, erosive tooth wear

INTRODUCTION

Accurate diagnosis of enamel and dentin lesions remains a critical challenge in pediatric dentistry, largely due to the milder structure of primary teeth¹⁻². Diagnostic inaccuracies may lead to inappropriate treatment decisions, unnecessary restorative cycles, increased healthcare costs, and long-term compromise of dental health. Therefore, early detection of both carious and non-carious lesions is essential for initiating preventive strategies and guiding minimally invasive interventions³⁻⁴.

Dental caries and erosive tooth wear (ETW) represent the most prevalent forms of hard tissue loss in children. Although indices such as the International Caries Detection and Assessment System (ICDAS) and the Basic Erosive Wear Examination (BEWE) are widely used for assessment⁵, their diagnostic reliability often depends on the examiner's experience and visual interpretation, introducing variability⁶. Similarly, while the Decayed, Missing, and Filled Teeth (DMFT) index remains a global standard, it lacks sensitivity for detecting early or non-cavitated lesions⁷⁻⁸. These early-stage lesions are critical for preventive-focused intervention but are frequently missed with conventional tools⁹. To address this, there is a growing interest in integrating complementary diagnostic technologies that enhance precision and reproducibility¹⁰.

ETW poses an additional diagnostic challenge in children due to its rapid progression and strong behavioral and dietary etiologies¹¹. Although the BEWE provides a straightforward grading framework, it may not fully reflect lesion severity or subtle progression over time¹². Furthermore, achieving sustained behavioral changes to reduce acid exposure remains a major clinical challenge¹³. Given these limitations, advanced diagnostic technologies are being explored to enhance accuracy, reproducibility, and early detection. three-dimensional (3D) intraoral imaging offers substantial diagnostic advantages. Intraoral scanners (IOS) capture surface data using structured light and high-resolution imaging, enabling detailed visualization of both carious and erosive lesions¹⁴⁻¹⁵. Unlike 2D imaging, 3D scans avoid

anatomical superimposition, improving lesion localization and characterization¹⁶. This is particularly valuable in primary teeth, where accurate and early detection can significantly impact the treatment trajectory. The advantages of IOS extend beyond diagnosis; they provide a radiation-free, non-invasive, and better tolerated by children. This technology also enables longitudinal digital record storage and facilitates clinician-caregiver communication¹⁵. Emerging systems incorporating fluorescence or near-infrared light further expand their diagnostic versatility¹⁷.

From an educational and clinical quality assurance perspective, integrating IOS into undergraduate dental curricula has been shown to strengthen diagnostic consistency, clinical training and standardization of care¹⁸⁻¹⁹.

Given these factors, combining conventional indices with IOS and other digital technologies could significantly improve early detection, reduce diagnostic variability, and support more effective clinical management of dental caries and ETW in primary teeth.

Therefore, the present in vitro study aimed to evaluate the diagnostic agreement between conventional visual examination and 3D-colored digital dental images obtained via intraoral scanning for the detection of dental caries and ETW in primary teeth.

MATERIALS AND METHODS

Ethical approval

All procedures in this study were conducted in accordance with the Declaration of Helsinki and applicable institutional and federal regulations governing research using human-derived biological materials. A convenience sample of extracted primary teeth with and without dental caries or erosive tooth wear was obtained from an institutional tooth repository supplied by voluntary donations from dentists nationwide, with use approved by the Indiana University Institutional Review Board (IRB #NS0911-07). Individual patient consent was not obtained because the investigators did not have access to donor identities; all teeth were collected, stored, and distributed by the repository in a fully de-identified manner. Donor anonymity and confidentiality were maintained throughout.

No sample size justification was performed prior to conducting the study. A post-hoc calculation showed that with the observed sample sizes and distributions of the visual scores for ICDAS and BEWE, the widths of the 2-sided 95% confidence intervals for the kappa statistics would be 0.15 and 0.25, which are reasonably precise estimates of kappa in an in vitro study.

Two independent in vitro experiments were conducted using extracted human primary molars with varying degrees of caries or ETW. For caries assessment, 233 molars were selected; while for ETW assessment, 164 molars were used. Teeth with restorations, fractures, or extensive structural damage unrelated to the lesion type under investigation were excluded. Each tooth was mounted in modeling wax, exposing the occlusal surface. Occlusal surfaces were selected for evaluation because they offer consistent morphology, are readily accessible for both visual and digital assessment, and provide a standardized and reproducible surface for in vitro scanning. All teeth were stored in a 0.1% thymol solution until use.

Assessment Criteria

- Lesion evaluation was performed using established clinical indices:
Dental caries: Scored according to the International Caries Detection and Assessment System (ICDAS), ranging from 0 (sound surface) to 6 (extensive cavity with visible dentine). Representative illustrative images are provided in Figure 1.
- ETW: Scored using the Basic Erosive Wear Examination (BEWE) index, ranging from 0 (no wear) to 3 (severe wear involving dentine loss). Representative illustrative images are provided in Figure 2.

The scoring criteria and corresponding lesion descriptions are summarized in Table 1.

Table 1. Diagnostic indices and scoring criteria used in the study

Condition	Index	Code	Description
Dental Caries	ICDAS	0	No visible lesion
		1	Initial caries, first visual change in enamel
		2	Distinct visual change in enamel
		3	Localized enamel breakdown, no visible dentine
		4	Underlying dark shadow from dentine
		5	Distinct cavity with visible dentine
		6	Extensive cavity with visible dentine
ETW	BEWE	0	No visible lesion

1	Mild erosive tooth wear: Initial surface texture loss
2	Moderate erosive tooth wear: Distinct defect, hard tissue loss involving less than 50% of the surface area.
3	Severe erosive tooth wear: Hard tissue loss involving more than 50% of the surface area. Moderate and severe levels may involve dentine exposure.

* ICDAS: International Caries Detection and Assessment System; BEWE: Basic Erosion Wear Examination

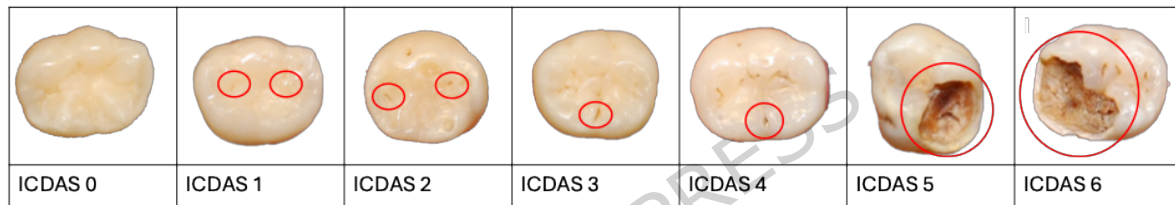


Figure 1. Image of a three-dimensional digital scan of primary molars providing a detailed visualization on occlusal surfaces of dental caries (white spots and darkened regions)

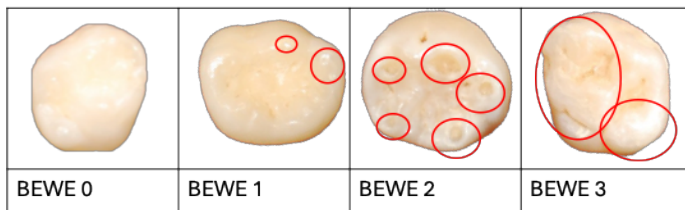


Figure 2. Image of a three-dimensional digital scan of primary molars providing a detailed visualization on occlusal surfaces of erosive tooth wear (loss of enamel).

Examination

Direct Visual Examination

Prior to visual assessment, each tooth was thoroughly air-dried using compressed air for approximately five seconds to optimize surface visibility. Occlusal surfaces of all primary molars were examined under standardized lighting conditions using an overhead dental unit light.

Visual inspections were conducted without magnification, following conventional clinical protocols. Lesions were assessed separately for dental caries and ETW. Carious lesions were scored using the ICDAS, and ETW was evaluated using the BEWE index, as detailed in Table 1.

Two calibrated examiners independently performed all assessments. Examiner training and calibration were conducted prior to data collection using typodont models arranged in proper anatomical order to form upper and lower arches, incorporating extracted teeth representative of the full range of lesion severity for each scoring system. Calibration was performed separately for the ICDAS and BEWE scoring systems, as each index is based on distinct diagnostic criteria and requires independent standardization. Inter-examiner reliability was established using kappa statistics, with a minimum threshold of 0.75 considered acceptable.

Examiners were blinded to the digital imaging data at the time of visual assessment to minimize bias. After scoring, data were recorded in a standardized collection sheet and securely stored for later comparison with the intraoral scanner results. A washout period of 24 hours was maintained between the direct and indirect evaluations to reduce recall bias.

Digital Scanning and Indirect Assessment

Following completion of the visual assessments, all teeth were scanned using a 3D IOS (TRIOS 4; 3Shape A/S, Copenhagen, Denmark) in accordance with the manufacturer's instructions. Prior to data collection, examiners were calibrated in the operation of the scanning system and associated analysis software (3Shape Unite).

Each primary molar was individually scanned with a focus on the occlusal surface. Teeth were coded and scanned in a controlled lighting environment, without the use of overhead dental lights, to prevent image distortion. The resulting digital files were analyzed using 3Shape Unite software on a 15.5-inch laptop display (Dell Inc.), allowing full-screen visualization of each tooth.

Each digital model was examined independently by calibrated examiners using the same indices applied during the visual examination (ICDAS and BEWE). The 3D images were systematically rotated and magnified to isolate and assess individual lesions. Occlusal surfaces were evaluated, and scoring was conducted in accordance with the criteria presented in Table 1.

Statistical Analysis

To evaluate the diagnostic agreement between direct visual examination and indirect assessment using IOS images, lesion scores for both ICDAS and BEWE were compared using the kappa statistic. In addition to kappa values, the percentage agreement between methods was also calculated. Analyses of dental caries and ETW were performed separately in SAS v9.4 (SAS Institute Inc., Cary, NC). A p-value of <0.05 was considered statistically significant.

RESULTS

Caries Detection (ICDAS)

Intra-examiner reliability for ICDAS scoring was substantial ($\kappa = 0.77$, $p < 0.0001$). As summarized in Table 2, agreement between the direct visual and IOS-based assessments was also within the substantial range ($\kappa = 0.64$, $p < 0.0001$). Higher concordance was observed for advanced caries stages, whereas early lesions showed lower agreement between direct and indirect assessments. Patterns of overestimation and underestimation by the indirect method relative to the direct assessment are detailed in Table 2.

Table 2. Agreement between visual examination and IOS-based assessment for ICDAS scores (n = 233).

ICDAS Score	Agreement (% / n)	Overestimation (% / n)	Underestimation (% / n)
0	36% (12)	64% (21)	0% (0)
1	61% (19)	35% (11)	3% (1)

2	64% (32)	10% (5)	26% (13)
3	52% (13)	0% (0)	48% (12)
4	100% (6)	0% (0)	0% (0)
5	96% (72)	4% (3)	0% (0)
6	92% (12)	0% (0)	8% (1)
Total	71% (166)	17% (40)	12% (27)

Kappa = 0.64 (substantial agreement); p-value < 0.0001. Overestimation = IOS score greater than visual score; Underestimation = IOS score lower than visual score.

ETW Detection (BEWE)

For ETW evaluation, intra-examiner reliability was substantial ($\kappa = 0.76$, $p < 0.0001$). Overall agreement between visual and IOS-based assessments was moderate ($\kappa = 0.58$, $p < 0.0001$), as presented in Table 3. Consistent with the behavior of early-stage lesions, lower agreement was observed for BEWE scores 0 and 1, while moderate lesions demonstrated the highest concordance. Patterns of overestimation and underestimation by the indirect method relative to the direct assessment for erosive wear are shown in Table 3.

Table 3. Agreement between visual examination and IOS-based assessment for BEWE scores (n = 164).

BEWE Score	Agreement (% / n)	Overestimation (% / n)	Underestimation (% / n)
0	47% (7)	53% (8)	0% (0)
1	42% (13)	52% (16)	6% (2)
2	99% (104)	1% (1)	0% (0)
3	62% (8)	0% (0)	38% (5)
Total	80% (132)	15% (25)	4% (7)

Kappa = 0.58 (moderate agreement); p-value < 0.0001. Overestimation = IOS score greater than visual score; Underestimation = IOS score lower than visual score.

DISCUSSION

This study demonstrated substantial diagnostic agreement between conventional visual examination and 3D-colored digital dental images for detecting both dental caries and erosive tooth wear (ETW) in primary teeth. These findings support the use of intraoral scanners (IOS) as a reliable adjunct in pediatric dental diagnostics, particularly for identifying moderate to advanced lesions. While existing literature predominantly focuses on permanent dentition, this original study is the first to evaluate IOS performance for the combined detection of caries and ETW in primary teeth. The unique characteristics of primary enamel such as being thinner, less mineralized, and more susceptible to demineralization¹⁹ introduce specific diagnostic challenges that have been largely overlooked in digital dentistry research.

The strong agreement observed at ICDAS scores 4-6 and BEWE score 2 aligns with previous studies indicating that IOS can effectively detect cumulative tissue loss. Schlenz et al.²⁰⁻²² reported the utility of IOS in tracking ETW progression over 12-, 24-, and 36-month intervals in young adults, demonstrating consistent surface loss measurements. Similarly, Machado et al.²³ validated the feasibility of using IOS to quantify ETW in vitro, emphasizing its potential for monitoring early surface change.

In line with our findings, Witecy et al.²⁴ and Charalambous et al.²⁵ reported that intraoral scanners are capable of identifying subtle enamel changes in both simulated and clinical environments. However, limitations persist in the detection of early lesions. Reduced agreement for ICDAS scores 0-2 and BEWE scores 0-1 in our study is consistent with findings by Michou et al.²⁶ and Charalambous et al.²⁷, who noted that IOS systems may have limited capability to consistently identify incipient enamel changes. These discrepancies may be influenced by optical smoothing algorithms, rendering thresholds, and enamel surface reflectivity, which can exaggerate early visual changes while masking moderate lesions, thereby contributing to overestimation at ICDAS 0-1 and underestimation at ICDAS 2-3^{24,25}. Similarly, for ETW, very early surface texture loss often falls below the detection threshold of IOS systems, as minimal erosive changes may not be captured reliably by current scanning resolution and rendering algorithms, which likely contributes to the lower agreement observed for BEWE scores 0-1^{24,26}. Recent studies have reinforced the diagnostic validity of IOS in primary teeth. Daneris et al.²⁸ confirmed high diagnostic performance of 3D IOS images for caries detection using ICDAS criteria, while Jones et al.²⁹ demonstrated successful application of deep learning to IOS-derived datasets, yielding diagnostic accuracy comparable to expert clinical evaluations in pediatric populations.

Primary teeth present unique diagnostic challenges due to their reduced enamel thickness and accelerated lesion progression. These features underscore the need for timely and sensitive detection methods. IOS offers

several advantages in pediatric care: it is non-invasive, radiation-free, and better tolerated by young patients. Additionally, digital scans facilitate longitudinal monitoring and can be used to communicate clinical findings with caregivers, contributing to improved diagnostic consistency and treatment planning. However, because the study was conducted under highly controlled in vitro conditions including ideal lighting, absence of saliva, and stable tooth positioning, diagnostic agreement may be artificially elevated compared with real clinical environments, particularly for early-stage lesions.

The integration of intraoral scanning technologies into routine pediatric care has important public health implications. Early detection and monitoring of dental caries and ETW may help reduce disease burden in children, particularly in underserved populations, while the non-invasive and radiation-free nature of IOS supports their potential use in community-based and telehealth settings. These benefits reflect a broader integration of IOS into clinical and epidemiological frameworks. Eggmann and Blatz¹⁷ describe the evolution of IOS into multi-functional diagnostic platforms, incorporating technologies such as fluorescence and near-infrared imaging to expand their diagnostic scope for caries and ETW. Despite these advances, technical and operational constraints remain. Variability in scan alignment³⁰, software capabilities, and examiner interpretation may influence reproducibility, particularly in early-stage lesions. The reduced agreement observed in lower scores within this study highlights the need for standardized imaging protocols and enhanced examiner training.

Despite promising results, several technical and clinical considerations must be addressed to optimize the diagnostic performance of intraoral scanners in pediatric dentistry. The reduced agreement observed in early-stage lesions highlights the need for improved agreement, whether through algorithm refinement, adjunctive technologies such as fluorescence or near-infrared imaging, or enhanced surface subtraction protocols. Examiner calibration and standardization of image interpretation also remain critical, as variability in screen resolution, lighting conditions, and 3D model manipulation can influence diagnostic outcomes. The potential integration of automated analysis tools, including AI-based lesion detection, may help reduce subjectivity and improve reproducibility across clinical settings.

In addition to these technical factors, several limitations of the present study should be acknowledged. First, the in vitro design excluded key clinical variables such as saliva, patient movement, and intraoral lighting variability, which may have artificially enhanced image clarity and diagnostic performance. Second, assessments were limited to the occlusal surfaces of primary molars, and further investigation across interproximal and smooth surfaces is warranted to validate broader clinical applicability. Third, although examiners were calibrated, the use of consensus scoring may not fully replicate real-world variability in independent clinical judgment. Lastly,

the use of a single scanner model and software version may limit generalizability, as hardware and software differences across IOS systems could influence performance and reproducibility. Consideration of training infrastructure and cost barriers is also essential for equitable implementation in diverse clinical environments.

Future in vivo studies involving a wider range of surfaces, patient age groups, and clinical conditions are necessary to validate and refine IOS-based diagnostic protocols for pediatric dentistry.

This study demonstrates that 3D digital imaging via intraoral scanners offers substantial diagnostic agreement with conventional visual methods for detecting occlusal caries and erosive tooth wear in primary teeth, particularly in moderate to advanced lesions. It is important to emphasize that this study evaluated agreement between diagnostic methods rather than diagnostic accuracy. Sensitivity and specificity were not calculated, and the visual examination served as a subjective reference standard. Therefore, findings related to early-stage lesions should be interpreted as reflecting inter-method discordance rather than reduced diagnostic sensitivity. While current limitations in early lesion detection persist, the findings support the integration of IOS as a complementary diagnostic tool in pediatric dentistry, aiding lesion monitoring, clinical decision-making, and minimally invasive care. Continued advances in imaging protocols, examiner training, and technological sensitivity will be essential to expand diagnostic performance. Until further technological refinement and standardization are achieved, IOS use should complement, rather than replace, traditional diagnostic approaches.

In conclusion, the current study affirms the substantial diagnostic potential of 3D digital scans for detecting caries and ETW in primary teeth, especially in moderate to severe stages. These findings align with a growing body of evidence advocating for digital tools in pediatric preventive dentistry. However, their use should be complemented with traditional methods until standardization and agreement for early lesion identification improve.

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This research received no external funding.

DATA AVAILABILITY

The study reports only concordance results, which are entirely included in this article. No additional datasets were generated or analyzed.

CONTRIBUTIONS

A.C. and A.T.H. conceived and designed the study. A.C. supervised the overall project. A.C.V.-T. was responsible for indices and scanning training and drafted the manuscript. G.H., B.S., and I.W. contributed to data acquisition. P.F.C. performed the statistical analysis and data interpretation. A.C. wrote the final version of the manuscript. All authors reviewed, revised, and approved the final manuscript.

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