J Orofac Orthop
https://doi.org/10.1007/s00056-019-00194-6

ORIGINAL ARTICLE

Use of a laser fluorescence device for the in vitro activity assessment of incipient caries lesions

Anahita Jablonski-Momeni[1] · Maria Rüter[1] · Juliane Röttker[1] · Heike Korbmacher-Steiner[1]

Received: 9 April 2019 / Accepted: 3 August 2019

Abstract

Purpose To evaluate the progression of demineralization during orthodontic treatment, the assessment of lesion activity is important in addition to the detection of lesion extent. This study aimed to evaluate the ability of laser fluorescence measurements to differentiate between active and inactive initial lesions in vitro.

Methods In all, 63 extracted, permanent human teeth were available for the study. On each occlusal investigation site, surface extent and activity of caries lesions were classified visually using ICDAS/ICCMS (International Caries Detection and Assessment System/International Caries Classification and Management System) criteria, following laser fluorescence measurements. Teeth were hemisected and assessed for lesion depth. Methyl red dye was applied to validate lesion activity on the sections. A Mann–Whitney U-test was performed to evaluate differences between laser fluorescence measurements for active and inactive lesions. For visual and laser fluorescence findings, diagnostic accuracy (Az, sensitivity and specificity) were calculated.

Results A total of 19 sound surfaces and 44 surfaces with ICDAS codes 1/2 were classified visually. The differences in laser fluorescence measurements between active and inactive lesions were not significant for the initial lesions ($p > 0.05$). Sensitivity/specificity for lesion depth was 90.5/92.3% (Az = 0.894), respectively, for visual assessment and 69.1/76.9% (Az = 0.745), respectively, for laser fluorescence. Sensitivity/specificity for activity assessment was 68.6/85.0% (Az = 0.768) for the visual method. For laser fluorescence measurements, no diagnostic accuracy values could be calculated for caries activity assessment.

Conclusion The visual detection and activity assessment of initial lesions was more suitable than the laser fluorescence method. Based on the results of this in vitro study, use of laser fluorescence cannot be recommended for distinguishing between active and inactive initial caries lesions on occlusal surfaces.

Keywords Enamel caries · Caries activity · International Caries Detection and Assessment System · International Caries Classification and Management System

Einsatz eines Laserfluoreszenzverfahrens zur Erfassung der Aktivität von initialen kariösen Läsionen in vitro

Zusammenfassung

Ziel Zur Bewertung einer Progression von kariösen Läsionen im Rahmen festsitzender kieferorthopädischer Behandlungen ist neben der Ausdehnung auch die Aktivität einer Läsion relevant. Ziel der vorliegenden Studie war es zu ermitteln, ob eine Differenzierung von aktiven und inaktiven initialen Läsionen mittels Laserfluoreszenzmessungen möglich ist.

✉ Prof. (apl.) Dr. med. dent. Anahita Jablonski-Momeni
momeni@staff.uni-marburg.de

[1] Dental School, Department of Orthodontics, Philipps-University Marburg, Georg-Voigt Str. 3, 35039 Marburg, Germany

Published online: 07 October 2019

Materialien und Methoden Insgesamt 63 extrahierte, permanente posteriore humane Zähne waren für diese Studie verfügbar. Je Okklusalfläche wurden Ausdehnung und Aktivität visuell nach den ICDAS/ICCMS(International Caries Detection and Assessment System/ International Caries Classification and Management System)-Kriterien untersucht und mittels Laserfluoreszenzverfahren gemessen. Die Zähne wurden am Messpunkt geteilt und histologisch untersucht. Zur Beurteilung der Läsionsaktivität wurde Methylrot verwendet. Mittels Mann-Whitney-U-Test wurde überprüft, ob Unterschiede zwischen Laserfluoreszenzmessungen für aktive und für inaktive Läsionen vorlagen.

Ergebnisse Visuell wurden 19 kariesfreie Okklusalflächen und 44 Flächen mit ICDAS-Codes 1 oder 2 klassifiziert. Für die Laserfluoreszenzmessungen waren die Unterschiede zwischen aktiven und inaktiven Läsionen für initiale Läsionen nicht signifikant ($p>0{,}05$). Für die visuelle Detektion der Läsionstiefe waren Sensitivität und Spezifität 90,50 bzw. 92,3% (AUC [„area under the curve“] = 0,894). Die korrespondierenden Werte für das Laserfluoreszenzverfahren lagen bei 69,1% für die Sensitivität und bei 76,9% für die Spezifität (AUC = 0,745). Sensitivität und Spezifität für die Erfassung der Läsionsaktivität waren 68,6 bzw. 85,0% (AUC = 0,768). Für Laserfluoreszenzmessungen konnten keine Werte zur diagnostischen Güte ermittelt werden.

Schlussfolgerungen Das visuelle Verfahren war für die Ermittlung der Läsionstiefe und der Erfassung der Läsionsaktivität besser geeignet als die Laserfluoreszenz. Basierend auf den Ergebnissen dieser In-vitro-Studie kann der Einsatz von Laserfluoreszenz nicht für die Unterscheidung zwischen aktiven und inaktiven initialen Läsionen empfohlen werden.

Schlüsselwörter Initiale Karies · Läsionsaktivität · International Caries Detection and Assessment System · International Caries Classification and Management System

Introduction

Oral biofilms on dental hard and soft tissues are the main cause of dental diseases, including caries and periodontal disease. According to data of a meta-analysis the incidence of new caries lesions formed during orthodontic treatment was 45.8% [39]. With regard to the severity of white spot lesions, it was reported that 63.3% of patients had mild lesions, but the remaining were affected severely with (26.9%) and without (9.9%) cavitations after treatment with multibracket appliances [11]. Bands and brackets appliances make the maintenance of oral hygiene difficult and provide additional surfaces to which bacteria can adhere and form a pathogenic biofilm, which causes white spot lesions and gingival inflammation. Due to the mostly difficult oral hygiene conditions during fixed orthodontic treatment, it can also be assumed that occlusal surfaces will not be adequately cleaned, thus, also favoring the development of demineralization in these areas. Management strategies usually focus on remineralization or on minimally invasive camouflage of the lesions [37]. Still, in patients with low or moderate caries risk, sufficient domestic dental hygiene with fluoride toothpaste should be emphasized [26]. Gingivitis during orthodontic treatment is often temporary and rarely progresses to periodontitis, although biofilms on retention sites increase the risk for periodontitis [34]. However, sufficient dental hygiene can keep the gingiva free from inflammation during orthodontic treatment with fixed appliances [26].

It is commonly accepted that dental caries is a dynamic process starting from the initial level of enamel demineralization through dentinal involvement and eventual cavitation; the dynamic balance between demineralization and remineralization determines the end result [12]. Generally demineralization can be stopped by adequate oral biofilm control, limitation of sugar consumption and the use of fluoridated agents. Thus, a carious lesion can be “active”, i.e., the demineralization process is in progress, or “inactive”, i.e., the demineralization process is interrupted [10, 30]. As an essential basis of the decision-making process, the diagnosis includes detection (presence versus absence of lesions), severity assessment (presence versus absence of cavitation), and activity assessment (active versus inactive) [33]. The latter is of high relevance since active caries lesions are at a greater likelihood of progression than inactive or arrested caries lesions [33]. Hence, it may lead to mostly avoidable operative treatments when the activity of a lesion is not considered.

For clinical daily use, it is beneficial to use procedures that detect and assess both caries extent and activity of a lesion. The visual criteria of the International Caries Detection and Assessment System (ICDAS) were shown to be an accurate and reproducible method to detect early lesions and also to detect changes in longitudinal follow-up [13, 25]. The ICDAS codes were also shown to be feasible for the detection of white spot lesions in orthodontic patients [2, 26] The ICDAS codes can be classified further using the criteria of the International Caries Classification and Management System (ICCMS) for lesion activity assessment [33].

Laser fluorescence measurement is another established device-based method for the detection of demineralization during orthodontic treatment [1, 38]. An established system is the DIAGNOdent (KaVo, Biberach, Germany), which emits red light (at a wavelength of 655 nm). The light is transmitted to the tooth surface by an excitation optical fiber and tip. Fluorescent light emitted by oral bacterial metabolites is captured by the device, incident light is filtered out, and the fluorescence intensity is translated to a numerical scale which ranges from 0 to 99. This method allows quantification of caries extent and depth and can be used as an adjunct to the visual caries detection [14, 28]. However, it has not been clearly described yet if laser fluorescence measurements can distinguish between active and inactive caries lesions. Therefore, the aim of the present study was to investigate the diagnostic accuracy of laser fluorescence measurements compared to ICDAS and ICCMS criteria for caries detection and activity assessment on occlusal surfaces of permanent teeth.

Materials and methods

The use of extracted teeth was approved by the responsible ethics committee (Ref. No. 64/15). Based on previously performed studies, sample size calculation was performed using the program G*Power, Version 3.1. A sample size of 36 teeth was calculated for a power of 0.9 (medium effect size, $\alpha = 0.05$). A dropout rate of 10% was added on, so that 40 teeth were planned as the minimum to include in the study.

The teeth were stored in a 0.001% sodium azide solution directly after extraction. Later, the teeth were thoroughly cleaned using a rotating brush and a cleaning paste (Clinpro Prophy Paste, 3M ESPE, Seefeld, Germany) and were stored in deionized water. Further examinations took place within 7–10 days after extraction of the teeth.

Sample selection and visual examination

Permanent teeth with sound surfaces or incipient occlusal lesions were included in the study. Care was given to exclude all teeth with developmental defects or other opacities. Prior to the cleaning procedure, each occlusal surface was examined for the presence of thick plaque. On each tooth, one site within the pit and fissure system was chosen as an investigation site by two experienced examiners.

For each investigation site the extent and the activity of the caries lesion were assessed using the ICDAS [18] and ICCMS [33] classification (Table 1).

Laser fluorescence measurements

Examination of the tooth surfaces was performed with the laser fluorescence (LF) DIAGNOdent 2095 (KaVo, Biberach, Germany) by one examiner experienced with the method [19, 22, 24]. The device was first calibrated in accordance with the manufacturer's instructions using a ceramic standard. For each tooth the device was first zeroed on an obviously caries-free enamel spot (zero value). For the measurements, tip A of the device was moved along the surface of each investigation site, and the peak value was recorded. Intraexaminer reproducibility was assessed by repeated measurements for all investigation sites, and the intraclass correlation coefficient (ICC) was calculated (0.96, 95% confidence interval 0.94–0.97). For further calculations, the laser fluorescence values were categorized [27]:

- Category 0 = LF values 0–7, caries-free enamel surface
- Category 1 = LF values 8–14, caries extending up to halfway through the enamel
- Category 2 = LF values 15–24, caries in the inner half of enamel
- Category 3 = LF values >24, caries in dentine

Histological preparation and examination

From each tooth, histological sections were produced following a standardized protocol [21]. In brief, the crown was cut at the investigation site and lesion depth was assessed under a microscope at 10× magnification (Zoom System: Leica Z6 APO; connected camera: Leica DFC 420; software: QWin Standard, V 3.4.0). To each face of the section, a histological score ([25]; Table 1) was given. For further analysis, the worst score was taken as the definitive score based on a consensus decision by two examiners.

As an established reference standard for the assessment of caries activity, methyl red solution at a concentration of 0.1% was applied to the histological sections according to already published protocols [21, 29] and consensus decisions were made. This indicator demonstrates a defined color change at a pH value around 5.5 on histological sections: Active lesions are likely to have a pH lower than 5.5, resulting in a red color, while inactive lesions mostly turn yellow at a pH more than 5.5.

Statistical evaluation

The statistical evaluation was performed using MedCalc statistical software version 17.4. Box plot diagrams were created by the software IBM SPSS Statistics, 24.

Correlation between methods was calculated using Spearman's rank correlation coefficient (r_s). The Mann–Whitney U-test was performed in order to evaluate whether there were significant differences between LF values for active and inactive lesions.

The histology results (lesion depth) were used to calculate sensitivity (SE), specificity (SP) and positive and negative predictive values (PPV and NPV, respectively) for the

Table 1 Classification of ICDAS/ICCMS caries codes and the histological classification
Tab. 1 Klassifikation der ICDAS/ICCMS-Codes und der histologischen Einteilung

ICDAS criteria for caries lesion extent [18]	
ICDAS code 0	Sound tooth surfaces, show no evidence of visible caries (no or questionable change in enamel translucency) when viewed clean and after prolonged air-drying (5 s)
ICDAS code 1	First visual change in enamel: opacity or discoloration (white or brown) after prolonged air drying, which is not seen on a wet surface
ICDAS code 2	Distinct visual change in enamel: opacity or discoloration distinctly visible when wet, lesion must still be visible when dry
ICCMS criteria for caries lesion activity [33]	
Signs of active caries lesions	Surface of enamel is whitish/yellowish; opaque with loss of luster, feels rough when the tip of the ball-ended probe is moved gently across the surface. The lesion may be covered by thick plaque prior to cleaning
Signs of inactive caries lesions	Surface of enamel is whitish, brownish or black. Enamel may be shiny and feels hard and smooth when the tip of the ball-ended probe is moved gently across the surface. The lesion may not be covered by thick plaque prior to cleaning
Histological classification [25]	
Score 0	No enamel demineralization or a narrow surface zone of opacity (edge phenomenon)
Score 1	Enamel demineralization limited to the outer 50% of the enamel layer
Score 2	Demineralization involving the inner 50% of the enamel, up to the enamel-dentine junction

ICDAS International Caries Detection and Assessment System, *ICCMS* International Caries Classification and Management System

ICDAS caries codes and the laser fluorescence measurements. The areas under the receiver operating characteristic (ROC) curves (Az) of visual and bioluminescence methods were compared using nonparametric tests [15]. For the visual activity assessment, the histology results after application of methyl red dye were used to create a ROC curve. The significance level was set at $\alpha = 0.05$.

Results

In total, 63 extracted permanent posterior teeth (49 molars, 14 premolars) were available for the study. The teeth were extracted due to periodontal disease, caries or orthodontic indications. The occlusal investigation sites were classified visually as follows: 19 sound surfaces, 26 surfaces with ICDAS code 1 and 18 surfaces with ICDAS code 2.

In Table 2, the distribution of the teeth according to the caries and activity classification (ICDAS and ICCMS) is shown, cross-tabulated with the results of the LF measurements. The suffix + or – indicates an active or inactive lesion, respectively. Visually inactive or sound sites were seen in 19 (30.2%) of the investigation sites. Of those, 16 (84.2%) were found to be without any signs of caries lesion using LF. The corresponding box plots are displayed in Fig. 1. The difference in LF measurements between active and inactive lesions was not significant for either ICDAS code 1 ($p = 0.282$) or ICDAS code 2 lesions ($p = 0.717$).

A significant positive correlation ($p < 0.0001$, 2-tailed test) was found between visual and LF findings for caries detection (r_s 0.804).

Due to damage caused by sectioning, eight investigation sites could not be included in further analyses. Of those, three investigation sites were classified as visually sound (ICDAS 0), four were ICDAS code 1 and one was ICDAS 2. Hence, a total of 55 teeth were still available for the assessment of lesion depth and activity using histology.

In Figs. 2 and 3, representative images of active and inactive lesions and the corresponding histological images are displayed. In Table 3, the distribution of the histology scores is cross-tabulated with the ICDAS/ICCMS codes and the LF measurements.

Table 2 Distribution of ICDAS/ICCMS caries codes cross tabulated with the results of the laser fluorescence measurements. The suffix + or – indicates an active or inactive lesion
Tab. 2 Kreuztabellierung der ICDAS/ICCMS-Karies-Codes mit den Befunden der Laserfluoreszenzmessungen. Der Zusatz + oder – weist auf eine aktive bzw. inaktive kariöse Läsion hin

LF measurement [a]	ICDAS/ICCMS code					*N* total
	0	1–	1+	2–	2+	
0 = LF values 0–7	16	1	8	0	0	25
1 = LF values 8–14	3	6	11	1	4	25
2 = LF values 15–24	0	0	0	6	5	11
3 = LF values >24	0	0	0	0	2	2
N total	19	7	19	7	11	63

[a] According to [27]
ICDAS International Caries Detection and Assessment System, *ICCMS* International Caries Classification and Management System, *LF* laser fluorescence

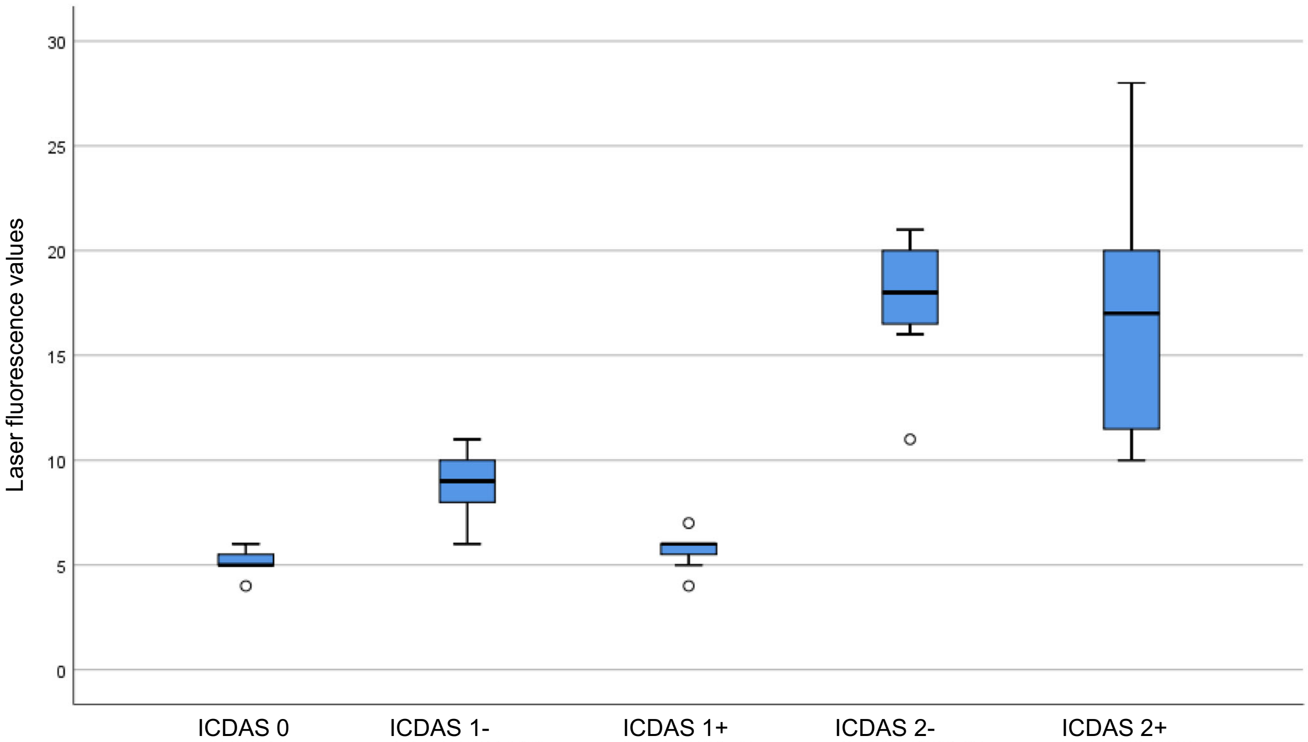

Fig. 1 Boxplots of International Caries Detection and Assessment System (*ICDAS*) findings and mean laser fluorescence (LF) values
Abb. 1 Boxplots der International Caries Detection and Assessment System (*ICDAS*) Ergebnisse und LF-Mittelwerte

Fig. 2 **a** Standard visible image of the occlusal surface of an extracted tooth with an International Caries Detection and Assessment System (ICDAS) 2+ lesion on the occlusal surface. Corresponding laser fluorescence (LF) value: 22 (category 2). **b**, **c** Corresponding histological sections
Abb. 2 **a** Aufnahme einer Okklusalfläche mit einer ICDAS(International Caries Detection and Assessment System)-2+-Läsion. Der korrespondierende LF(Laserfluoreszenz)-Wert beträgt 22 (Kategorie 2). **b**, **c** Korrespondierende histologische Schnitte

Figure 4 shows the ROC curves for visual and LF findings using histology as a reference standard. Figure 5 shows the ROC curve for visual findings using methyl red dye as a reference standard for activity assessment. For the LF measurements, no diagnostic accuracy could be calculated with regard to caries activity assessment since no cut-off point could be set for the differentiation between active and inactive lesions.

Table 4 shows the corresponding areas under the curves, sensitivity (SE), specificity (SP), and the predictive values for the visual and LF findings. The performance of visual caries detection (ICDAS codes) showed higher results for SE, SP and predictive values compared to LF measurements. A comparison of the areas under the curve (Az) of both methods also showed significant differences between the visual and LF method for caries detection ($p = 0.015$).

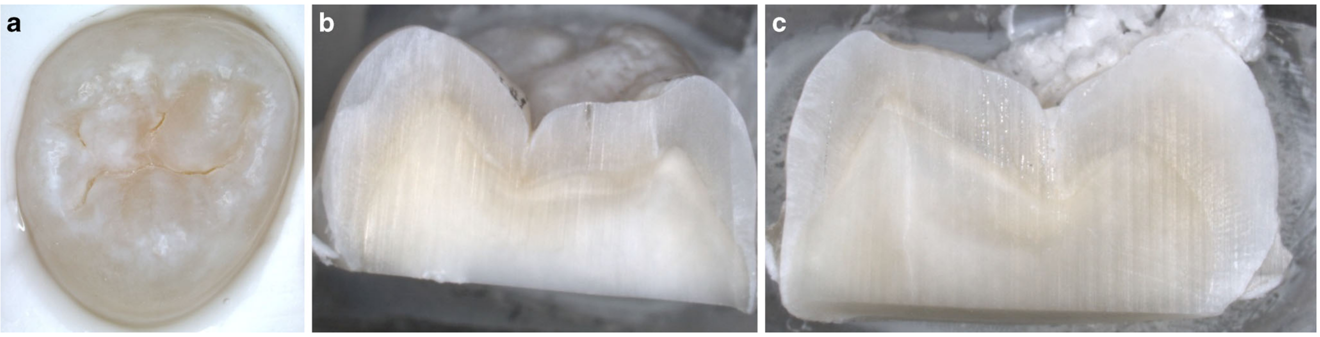

Fig. 3 **a** Standard visible image of the occlusal surface of an extracted tooth with an International Caries Detection and Assessment System (ICDAS) 1– lesion on the occlusal surface. Corresponding laser fluorescence (LF) value: 8 (category 1). **b**, **c** Corresponding histological sections
Abb. 3 **a** Aufnahme einer Okklusalfläche mit einer ICDAS(International Caries Detection and Assessment System)-1– -Läsion. Der korrespondierende LF(Laserfluoreszenz)-Wert beträgt 8 (Kategorie 1). **b**, **c** Korrespondierende histologische Schnitte

Table 3 Distribution of ICDAS/ICCMS caries codes and the LF measurements cross tabulated with the results of the histology for activity assessment after application of methyl red. The suffix + or – indicates an active or inactive lesion
Tab. 3 Kreuztabellierung der ICDAS/ICCMS-Karies-Codes und der LF-Befunde mit den Ergebnissen der Histologie nach Applikation von Metyhlrot. Der Zusatz + oder – weist auf eine aktive bzw. inaktive kariöse Läsion hin

	Histology scores (lesion activity)		*N* total
	Inactive	Active	
ICDAS/ICCMS code			
0	13	3	16
1–	3	2	5
1+	2	15	17
2–	1	6	7
2+	1	9	10
N total	20	35	55
LF measurement			
0 = LF values 0–7	14	9	23
1 = LF values 8–14	5	14	19
2 = LF values 15–24	1	10	11
3 = LF values >24	0	2	2
N total	20	35	55

ICDAS International Caries Detection and Assessment System, *ICCMS* International Caries Classification and Management System, *LF* laser fluorescence

Discussion

In the present study, the diagnostic performance of visual and laser fluorescence findings were examined with regard to activity assessment of demineralized tooth surfaces.

Far too often, caries diagnosis is only associated with the determination of the presence or absence of a carious lesion. However, assessment of the caries activity state is required in addition to caries lesion staging [17] in order to estimate whether a lesion is more or less likely to progress.

In patients with fixed orthodontic treatment, the region of the tooth surface around brackets is prone to adhesion of oral bacteria and subsequent biofilm formation, which is the main cause of dental diseases including caries [34]. It was reported that a single-time, self-performed manual brushing [40] is often insufficient and known to leave biofilm behind in retention sites like interproximal spaces, gingival margins, and fissures. Hence, caries detection is not only relevant to surfaces around brackets, but also on occlusal surfaces of permanent molars, which are typical caries predilection sites and at increased risk of lesion development due to a relatively long eruption period [6].

During fixed orthodontic treatment, occlusal surfaces are still better accessible than smooth surfaces with brackets, bands, wires or other attachments. Therefore, early caries detection in fissures and pits can decisively influence caries management involving the use of preventive treatment options once demineralization is diagnosed. This in turn can benefit all tooth surfaces.

Traditionally examiners assess caries lesion activity using visual and tactile criteria. No single factor is exclusively valid for defining activity [10], but certain indicators can be used as predictors for activity assessment. These are mainly the presence of plaque, tactile characteristics like surface roughness, and the tendency of gingiva to bleed [8, 9, 31].

For the detection of demineralization, the visual inspection of tooth surfaces using the ICDAS codes is a practicable method. It presents good diagnostic accuracy as determined by comparison with histological findings and high reproducibility among examiners [23, 25]. In the present study, the diagnostic accuracy of the ICDAS caries codes could be confirmed (Table 4). It was even significantly higher than that for the values obtained by laser fluorescence measurements. This might be due to the fact that examiners were experienced in the use of the visual caries detection system. It must also be taken into account that the use of laser fluorescence is always associated with the

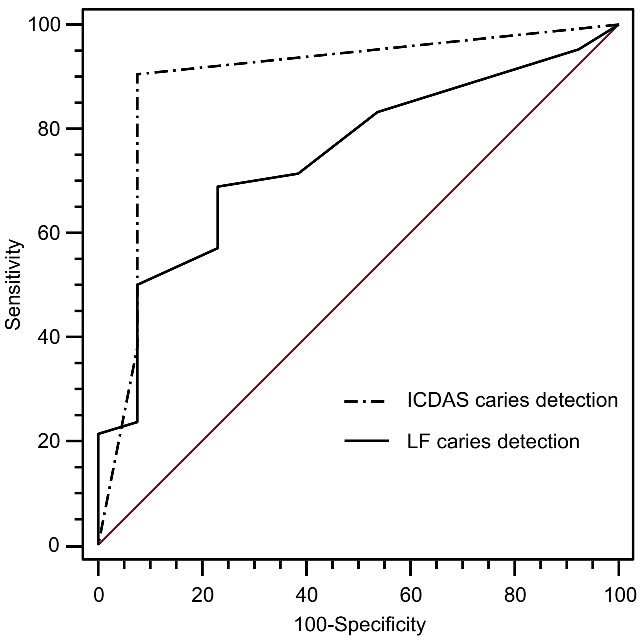

Fig. 4 Receiver operating characteristic (ROC) curves for visual and laser fluorescence caries detection using histology (lesion depth) as reference standard. *ICDAS* International Caries Detection and Assessment System, *LF* laser fluorescence
Abb. 4 ROC(„receiver operating characteristics“)-Kurven für visuelle Befunde und Laserfluoreszenzmessungen zur Kariesdetektion. Referenz: Bestimmung der Läsionstiefe an histologischen Schnitten. *ICDAS* International Caries Detection and Assessment System, *LF* laser fluorescence

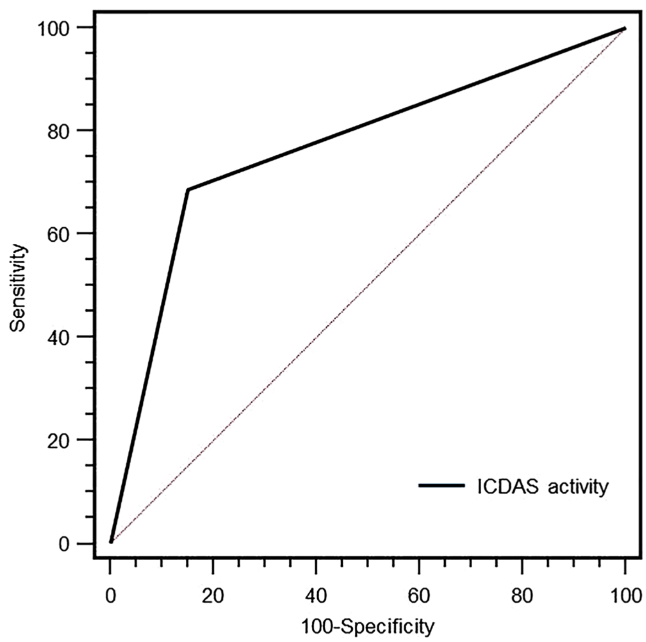

Fig. 5 Receiver operating characteristic (ROC) curve for visual activity assessment using histology (methyl red dye) as the reference standard. *ICDAS* International Caries Detection and Assessment System
Abb. 5 ROC(„receiver operating characteristics“)-Kurve für visuelle Befunde zur Kariesaktivitätserfassung. Referenz: Methylrotfärbung an histologischen Schnitten. *ICDAS* International Caries Detection and Assessment System

risk of false-positive results, and this might have led to the lower diagnostic accuracy compared to visual detection.

In addition to lesion depth, caries activity is an essential aspect of a carious lesion to be taken into account for appropriate treatment planning [7]. Besides the visual classification of caries and its activity assessment, different tools have been developed to support the assessment process and to quantify the extent and depth of carious changes in the tooth tissue. One example is the use of laser fluorescence devices (e.g., DIAGNOdent® and DIAGNOdent pen, KaVo, Biberach, Germany) [28], which have already shown promising results in caries detection [36]. The fluorescence read by the device stems probably from bacterial metabolic byproducts, especially porphyrins [5, 16]. Active lesions are more infected than inactive lesions [30], so it could be assumed that the laser fluorescence device would show higher values in active lesions. One aim of the present study was to evaluate the validity of LF in caries activity assessment. It was shown that differentiating between active and inactive initial lesions was not possible by LF ($p > 0.05$, Fig. 1). Based on the obtained data, no clear cut-off could be determined for distinguishing between active and inactive lesions, and ROC analysis could not be performed like for the detection of caries depth.

Table 4 Area under the ROC curve, sensitivity, specificity, and the predictive values for all methods. The 95% confidence interval in parentheses
Tab. 4 Fläche unter der ROC Kurve, Sensitivität, Spezifität und prädiktive Werte für alle Verfahren. In Klammern: 95%-Konfidenzintervall

	Az	Standard error	SN (%)	SP (%)	PPV (%)	NPV (%)
Laser fluorescence (cut off LF category 0/1)	0.745 (0.610;0.853)	0.072	69.1 (52.9;82.4)	76.9 (46.2;95.0)	90.6 (77.8;96.4)	43.5 (30.9;56.9)
ICDAS code (cut off ICDAS codes 0/1)	0.894 (0.781;0.961)	0.063	90.5 (77.4;97.3)	92.3 (64.0;99.8)	97.4 (85.2;99.6)	75.0 (53.8;88.5)
ICCMS code (cut off inactive/active)	0.768 (0.637;0.898)	0.066	68.6 (50.7;83.1)	85.0 (62.1;96.8)	88.9 (73.3;95.9)	60.7 (47.8;72.3)

Az Area under the receiver operating characteristic (ROC) curve, *SN* Sensitivity, *SP* Specificity, *PPV* positive predictive value, *NPV* negative predictive value, *LF* laser fluorescence, *ICDAS* International Caries Detection and Assessment System, *ICCMS* International Caries Classification and Management System

Braga et al. [4] have shown that the use of laser fluorescence on occlusal surfaces of primary molars could differentiate between active and inactive lesions. However, the authors described that LF readings were only significantly different between cavitated active and inactive caries. In general, cavitated lesions presented a higher level of infection [35], which contributed to the presence of a higher amount of bacterial metabolites and, consequently, higher LF readings. In the present study, only noncavitated lesions (ICDAS codes 1 and 2) were included, which might be a reason for the outcome being dissimilar from the results by Braga et al. [4].

In vivo studies have shown the ability of laser fluorescence measurements to distinguish active and inactive lesions on the smooth surfaces of permanent teeth [32]. However, the examinations were not performed in patients during orthodontic treatment, and the smooth surfaces were freely accessible. Other studies have shown the usefulness of laser fluorescence in assessing the regression of demineralization after the use of remineralization agents on smooth surfaces with and without orthodontic brackets [3, 19, 20].

Conclusion and clinical relevance

The results of the present study support the conclusion that visual caries detection and activity assessment on occlusal surfaces achieved good diagnostic accuracy in vitro. The laser fluorescence device performed well with regard to the detection of demineralization in general and can be used as an adjunct to objectify the findings, but it could not be used for caries activity assessment.

When initial demineralization develops, an assessment of the activity of lesions is beneficial with regard to early preventive management. This part of the caries diagnosis procedure can be performed efficiently using visual criteria in patients with orthodontic fixed appliances in visually accessible sites like occlusal surfaces without the aid of additional detection tools.

Compliance with ethical guidelines

Conflict of interest A. Jablonski-Momeni, M. Rüter, J. Röttker and H. Korbmacher-Steiner declare that they have no competing interests.

Ethical standards This article does not report on any studies with human participants that were performed by any of the authors. The use of extracted teeth was approved by the responsible ethics committee.

References

1. Aljehani A, Tranaeus S, Forsberg CM, Angmar-Månsson B, Shi XQ (2004) In vitro quantification of white spot enamel lesions adjacent to fixed orthodontic appliances using quantitative light-induced fluorescence and DIAGNOdent. Acta Odontol Scand 62:313–318
2. Almosa NA, Lundgren T, Aldrees AM, Birkhed D, Kjellberg H (2014) Diagnosing the severity of buccal caries lesions in governmental and private orthodontic patients at debonding, using the ICDAS-II and the DIAGNOdent Pen. Angle Orthod 84(3):430–436
3. Andersson A, Sköld-Larsson K, Hallgren A, Petersson LG, Twetman S (2007) Effect of a dental cream containing amorphous cream phosphate complexes on white spot lesion regression assessed by laser fluorescence. Oral Health Prev Dent 5(3):229–233
4. Braga MM, de Benedetto MS, Imparato JC, Mendes FM (2010) New methodology to assess activity status of occlusal caries in primary teeth using laser fluorescence device. J Biomed Opt 15(4):47005. https://doi.org/10.1117/1.3463007
5. Buchalla W (2005) Comparative fluorescence spectroscopy shows differences in noncavitated enamel lesions. Caries Res 39(2): 150–156
6. Carvalho JC, Ekstrand KR, Thylstrup A (1989) Dental plaque and caries on occlusal surfaces of first permanent molars in relation to stage of eruption. J Dent Res 68:773–779
7. Drancourt N, Roger-Leroi V, Martignon S, Jablonski-Momeni A, Pitts N, Doméjean S (2019) Carious lesion activity assessment in clinical practice: a systematic review. Clin Oral Invest. https://doi.org/10.1007/s00784-019-02839-7
8. Ekstrand KR, Bruun G, Bruun M (1998) Plaque and gingival status as indicators for caries progression on approximal surfaces. Caries Res 32:41–45
9. Ekstrand KR, Martignon S, Ricketts DJ, Qvist V (2007) Detection and activity assessment of primary coronal caries lesions: a methodologic study. Oper Dent 32:225–235
10. Ekstrand KR, Zero DT, Martignon S, Pitts NB (2009) Lesion activity assessment. In: Pitts NB (ed) Detection, assessment, diagnosis and monitoring of caries. Monographs in Oral Science, vol 21. Karger, Basel, pp 63–90
11. Enaia M, Bock N, Ruf S (2011) White-spot lesions during multibracket appliance treatment: a challenge for clinical excellence. Am J Orthod Dentofacial Orthop 140:e17–e24
12. Featherstone JD (2004) The continuum of dental caries—evidence for a dynamic disease process. J Dent Res 83(Spec No C):C39–C42
13. Ferreira Zandona A, Santiago E, Eckert G, Fontana M, Ando M, Zero DT (2010) Use of ICDAS combined with quantitative light-induced fluorescence as a caries detection method. Caries Res 44(3):317–322
14. Gomez J (2005) Detection and diagnosis of the early caries lesion. BMC Oral Health 15(Suppl 1):S3
15. Hanley JA, McNeil BJ (1983) A method of comparing the areas under receiver operating characteristic curves derived from the same cases. Radiology 148:839–843
16. Hibst R, Paulus R, Lussi A (2001) Detection of occlusal caries by laser fluorescence: basic and clinical investigations. Med Laser Appl 16:205–213
17. Authors of International Caries Classification and Management System (ICCMS), Ismail AI, Pitts NB, Tellez M, Banerjee A, Deery C, Douglas G, Eggertsson H, Ekstrand K, Ellwood R, Gomez J, Jablonski-Momeni A, Kolker J, Longbottom C, Manton D, Martignon S, McGrady M, Rechmann P, Ricketts D, Sohn W, Thompson V, Twetman S, Weyant R, Wolff M, Zandona A (2015) The International Caries Classification and Management System (ICCMS™). An Example of a Caries Management Pathway. Bmc Oral Health 15(Suppl 1):S9
18. Ismail AI, Sohn W, Tellez M, Amaya A, Sen A, Hasson H, Pitts NB (2007) The International Caries Detection and Assessment System (ICDAS): an integrated system for measuring dental caries. Community Dent Oral Epidemiol 35(3):170–178
19. Jablonski-Momeni A, Heinzel-Gutenbrunner M (2014) Efficacy of the "Self-assembling peptide P11-4" in the formation of a reminer-

alization scaffold on artificially induced enamel lesions on smooth surfaces. J Orofac Orthop 75:175–189
20. Jablonski-Momeni A, Korbmacher-Steiner H, Heinzel-Gutenbrunner M, Jablonski B, Jaquet W, Bottenberg P (2019) Randomised in-situ trial investigating self-assembling peptide matrix P_{11}-4 in the prevention of artificial caries lesions. Sci Rep 9:269. https://doi.org/10.1038/s41598-018-36536-4
21. Jablonski-Momeni A, Moos J, Sakhaei Manesh V, Stoll R (2018) Diagnostic accuracy of a new Caries Activity Imaging System for assessment of caries activity on occlusal surfaces. Caries Res 52:279–228
22. Jablonski-Momeni A, Ricketts DNJ, Rolfsen S, Stoll R, Heinzel-Gutenbrunner M, Stachniss V, Pieper K (2011) Performance of laser fluorescence at tooth surface and histological section. Lasers Med Sci 26:171–178
23. Jablonski-Momeni A, Ricketts DNJ, Weber K, Ziomek O, Heinzel-Gutenbrunner M, Schipper HM, Stoll R, Pieper K (2010) Effect of different time intervals between examinations on the reproducibility of ICDAS-II for occlusal caries. Caries Res 44:267–271
24. Jablonski-Momeni A, Rosen SM, Schipper HM, Stoll R, Roggendorf MJ, Heinzel-Gutenbrunner M, Stachniss V, Pieper K (2012) Impact of measuring multiple or single occlusal lesions on estimates of diagnostic accuracy using fluorescence methods. Lasers Med Sci 27:343–352
25. Jablonski-Momeni A, Stachniss V, Ricketts DNJ, Heinzel-Gutenbrunner M, Pieper K (2008) Reproducibility and accuracy of the ICDAS-II for detection of occlusal caries in vitro. Caries Res 42:79–87
26. Kirschneck C, Christl JJ, Reicheneder C, Proff P (2016) Efficacy of fluoride varnish for preventing white spot lesions and gingivitis during orthodontic treatment with fixed appliances—a prospective randomized controlled trial. Clin Oral Investig 20:2371–2378
27. Lussi A, Hellwig E (2006) Performance of a new laser fluorescence device for the detection of occlusal caries in vitro. J Dent 34:467–447
28. Lussi A, Hibst R, Paulus R (2004) DIAGNOdent: an optical method for caries detection. J Dent Res 83(Spec Iss C):C80–C83
29. MacGregor AB (1961) The position and extent of acid in carious process. Arch Oral Biol 4:86–91
30. Nyvad B, Fejerskov O (1997) Assessing the stage of caries lesion activity on the basis of clinical and microbiological examination. Community Dent Oral Epidemiol 25:69–75
31. Nyvad B, Machiulskiene V, Baelum V (1999) Reliability of a new caries diagnostic system differentiating between active and inactive caries lesions. Caries Res 33:252–260
32. Pinelli C, Campos Serra M, de Castro Monteiro Loffredo L (2002) Validity and reproducibility of a laser fluorescence system for detecting the activity of white-spot lesions on free smooth surfaces in vivo. Caries Res 36(1):19–24
33. Pitts NB, Ismail AI, Martignon S, Ekstrand K, Douglas G, Longbottom C (2014) ICCMS™ guide for practitioners and educators. Full guide. Available via DIALOG. http://www.iccms-web.com. Accessed 18 Mar 2019
34. Ren Y, Jongsma MA, Mei L, van der Mei HC, Busscher HJ (2014) Orthodontic treatment with fixed appliances and biofilm formation—a potential public health threat? Clin Oral Investig 18:1711–1718
35. Ricketts DN, Ekstrand KR, Kidd EA, Larsen T (2002) Relating visual and radiographic ranked scoring systems for occlusal caries detection to histological and microbiological evidence. Oper Dent 27(3):231–237
36. Rosa MI, Schambeck VS, Dondossola ER, Alexandre MC, Tuon L, Grande AJ, Hugo F (2016) Laser fluorescence of caries detection in permanent teeth in vitro: a systematic review and meta-analysis. J Evid Based Med 9(4):213–224
37. Sonesson M, Bergstrand F, Gizani S, Twetman S (2017) Management of post-orthodontic white spot lesions: an updated systematic review. Eur J Orthod 39:116–121
38. Staudt CB, Lussi A, Jacquet J, Kiliaridis S (2004) White spot lesions around brackets: in vitro detection by laser fluorescence. Eur J Oral Sci 112:237–243
39. Sundararaj D, Venkatachalapathy S, Tandon A, Pereira A (2015) Critical evaluation of incidence and prevalence of white spot lesions during fixed orthodontic appliance treatment: a meta-analysis. J Int Soc Prev Community Dent 5:433–439
40. Van der Weijden GA, Echeverria JJ, Sanz M, Lindhe J (2008) Mechanical supragingival plaque control. In: Lindhe J, Lang NP, Karring T (eds) Clinical periodontology and implant dentistry, 5th edn. Blackwell Munskgaard, Copenhagen, pp 705–733