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In-vitro-Validierung eines nahinfrarot-basierten Diagnosesystems für Interdentalkaries und in-vivo Reliabilität bei unterschiedlichen Beobachtern

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Abkürzungsverzeichnis

CCD	Charge-coupled Device
CMOS	Complementary metal-oxide-semiconductor
DIFOTI	Digital Imaging Fiber-Optic Transillumination
FOTI	Fiber-Optic Transillumination
HDR	High Dynamic Range
HDRI	High-dynamic-range imaging, Hochkontrastbildgebung
NIRT	Nahinfrarot-Transillumination
µCT	Mikro-Computertomografie

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Einleitung

Karies zählt auch heute noch zu den häufigsten Infektionserkrankungen und ist stark von der Lebensweise und dem Gesundheitsverhalten abhängig, welche wiederum durch sozioökonomische Faktoren, wie Schulbildung und Einkommen beeinflusst werden (Brauckhoff et al., 2009). Weltweit sind davon 60-90 % der Schulkinder und die überwiegende Mehrheit der Erwachsenen betroffen. Während in den industriell höher entwickelten Ländern durch Fortschritte in der Zahnheilkunde gute Präventionserfolge bei Karies erzielt werden konnten und damit vor allem bei Kindern die Inzidenz sinkt, steigt sie in den Entwicklungsländern weiter an (Petersen, 2003). Ursache für die Entstehung von Karies sind säureproduzierende Bakterien wie Streptokokken oder Laktobazillen, die sich in Plaque organisieren und durch die Metabolisierung von Kohlenhydraten Säuren erzeugen. Diese schädigen die Zahnhartsubstanzen. Von Bedeutung ist dabei vor allem die Häufigkeit der Kohlenhydrataufnahme sowie die Verweildauer im Mund (Brauckhoff et al., 2009; Burt et al., 1988).

Approximalkaries ist neben der Fissurenkaries die häufigste Kariesform im Seitenzahnbereich (Demirci, Tuncer, & Yuceokur, 2010). Sie wird zusätzlich durch die Retention von Speiseresten im Interdentalraum und die erschwerte Reinigung desselben begünstigt (Axelsson & Lindhe, 1978). Während die Fissurenkaries meist schon durch eine klinische Untersuchung diagnostiziert werden kann, lässt sich der Approximalraum aufgrund der Papillen und der benachbarten Zähne nur eingeschränkt einsehen. Somit ist eine approximale Läsion schwieriger zu diagnostizieren als Fissuren- oder Glattflächenkaries und wird oft erst entdeckt, wenn sie bereits fortgeschritten oder sogar kavitiert und damit bereits pulpanah ist (Poorterman, Aartman, & Kalsbeek, 1999). Eine nicht- oder mikroinvasive Kariestherapie mittels Anwendung von Fluoridlacken oder Kariesinfiltration ist in diesem Stadium nicht mehr möglich (Dorri, Dunne, Walsh, & Schwendicke, 2015). Die dann notwendige Versorgung mit direkten oder indirekten alloplastischen Werkstoffen schließt jedoch meist die Entfernung gesunder Zahnhartsubstanz ein.

Daher sind eine frühzeitige Erkennung und Überwachung von kariösen Läsionen notwendig.

Die Röntgendiagnostik mit kurzwelliger elektromagnetischer Strahlung wird seit über 100 Jahren als ergänzende Technik zur Diagnose von kariösen Läsionen eingesetzt. Zur Kariesdiagnostik werden häufig sogenannte Bissflügelaufnahmen verwendet, bei der die Zahnkronen der rechten oder linken Molaren und Prämolaren dargestellt werden können (Raper, 1925). Vorteile sind unter anderem die Möglichkeit die Läsionstiefe in mesio-distaler und okkluso-apikaler Richtung darzustellen sowie die Aufnahmen zur Verlaufskontrolle archivieren zu können. Bei der digitalen Radiografie kann man zudem den Kontrast und die Helligkeit der Aufnahmen nachträglich anpassen, auch kann die Strahlendosis im Vergleich zum analogen Röntgen deutlich reduziert werden. Allerdings gibt es auch Nachteile und Limitationen. Aufgrund der geringen Sensitivität ist die Röntgendiagnostik nicht für eine frühzeitige Erkennung von Karies geeignet (Abesi et al., 2012). Zudem kommt es in den Aufnahmen oft zu Überlagerungseffekten oder Artefakten, die die Diagnostik erschweren, da es sich um eine zweidimensionale Projektion des dreidimensionalen Gewebes, eine Summationsaufnahme, handelt. Aufgrund der ionisierenden Strahlung lassen sich Röntgenaufnahmen nicht beliebig oft wiederholen und sind nicht für eine engmaschige Überwachung geeignet. Auch muss für eine gute Vergleichbarkeit im Rahmen von Monitoring immer der gleiche Aufnahmewinkel getroffen werden. Daher wurde schon vor vielen Jahren auf die Notwendigkeit neuer Diagnostikmethoden aufmerksam gemacht (Featherstone, 1999; Hume, 1993).

Die Transillumination von Gewebe zu diagnostischen Zwecken, auch Diaphanoskopie genannt, wurde bereits vor Entdeckung der Röntgenstrahlung in der Allgemeinmedizin angewandt (Blegvad, 1957). Auch in der Zahnmedizin ist sie mittlerweile ein probates Mittel zur Kariesdiagnostik, da sich die optischen Eigenschaften von gesunder und demineralisierter oder kariöser Zahnhartsubstanz unterscheiden. Durch Lichtstreuung in der porösen Struktur von demineralisiertem Schmelz können kariöse Läsionen visualisiert werden und erscheinen bei der Transillumination als dunkle Schatten. Die Transillumination mit hochintensivem Weißlicht und einem Lichtleiter wird auch als faseroptische Transillumination (FOTI, Fiber-Optic Transillumination) bezeichnet und wurde bereits 1970 beschrieben (Friedman & Marcus, 1970). Ein Nachteil dieser Methode war die mangelnde Möglichkeit der Dokumentation. Die darauffolgende Weiterentwicklung DIFOTI (Digital Imaging Fiber-Optic Transillumination) kombinierte FOTI mit einer CCD-Kamera. So konnten digitale Bilder von okklusal oder der der Lichtquelle gegenüberliegenden Seite aufgezeichnet werden und anschließend an einem Bildschirm befundet werden. Ein Nachteil war, dass das Licht in Richtung der Kamera ausgestrahlt wurde und es so öfters zu überbelichteten Bildern kam.

Untersuchungen der optischen Eigenschaften von Schmelz und Dentin zeigten einen Vorteil für Licht im Nahinfrarotbereich gegenüber Weißlicht bei der Transillumination. Es konnte gezeigt werden, dass Licht mit höheren Wellenlängen im Schmelz weniger gestreut wird als Weißlicht. Im Dentin blieb die Streuung mit zunehmender Wellenlänge jedoch fast unverändert hoch (D. Fried, Glena, Featherstone, & Seka, 1995; Jones & Fried, 2002). Dies begründet sich darin, dass die Dentintubuli im Dentin als Mie-Streuer wirken (Vaarkamp, ten Bosch, & Verdonschot, 1995; Zijp & ten Bosch, 1991). In den meisten Fällen lässt sich daher eine Läsion im Dentin nicht eindeutig durch Transillumination darstellen.

Fried und Jones ließen sich 2006 die Nahinfrarot-Transillumination (NIRT) zur Kariesdiagnostik im Bereich von 795 -1600 nm patentieren (Daniel Fried & Jones, 2006). Im Jahr 2012 kam das erste kommerziell erhältliche Diagnostiksystem mit Nahinfrarot-Transillumination auf den Markt (DIAGNOcam, KaVo, Biberach, Deutschland). KaVo verwendete einen Laser mit 780 nm und lag damit knapp unter dem patentierten Wellenlängenbereich. In den USA wurde das Gerät unter dem Namen CariVu (Dexis, Hatfield, USA) mit einer modifizierten Software eingeführt. Andere Hersteller verwendeten statt der Transillumination das Prinzip der Reflexion und konnten so eine Wellenlänge von 850 nm verwenden (VistaCam, Dürr Dental, Bietigheim-Bissingen Deutschland).

Bei der DIAGNOcam wird Laserlicht mit einer Leistung von 1 mW und einer Wellenlänge von 780 nm durch einen flexiblen Leiter von bukkaler und oraler Seite durch die Gingiva, den Alveolarfortsatz in die Zahnwurzel gestrahlt. Das Dentin wirkt als Lichtleiter und leitet das Licht zur Krone, wo das Dentin als diffuse Lichtquelle dient, die das Licht durch den Schmelz nach außen leitet (Kienle & Hibst, 2006). Das Live-Bild einer von okklusal auf den Zahn gerichteten CMOS-Kamera kann in der KaVo KiD Software visualisiert und einzelne Bilder aufgezeichnet werden.

In mehreren klinischen Studien wurde die DIAGNOcam mit Röntgendiagnostik verglichen (Abdelaziz & Krejci, 2015; Baltacioglu & Orhan, 2017; Berg, Stahl, Lien, Slack, & Vandewalle, 2018; Kühnisch et al., 2016; Ozkan, Kanli, Baseren, Arslan, & Tatar, 2015; Söchtig, Hickel, & Kühnisch, 2014). Dort zeigte die DIAGNOcam eine vergleichbare bis überlegene Eignung zur Kariesdiagnostik. Die niedrige Sensitivität der Röntgendiagnostik macht diese zur Validierung jedoch nur begrenzt geeignet. Daher wurden in einzelnen Studien die diagnostizierten, behandlungsbedürftigen Läsionen eröffnet, um eine genauere Aussage über die Tiefe geben zu können (Baltacioglu & Orhan, 2017; Ozkan et al., 2015). Dies ist jedoch auch keine besonders genaue Validierungsmethode.

Der Vorteil von in-vitro-Untersuchungen ist, dass die Zähne entweder histologisch aufbereitet und die Läsionstiefe im Mikroskop in Schnitten beurteilt werden können, oder aber mittels Mikro-Computertomografie (µCT) untersucht werden können. Die histologische Aufbereitung hat den Nachteil, dass die Proben dabei zerstört werden müssen und man nur mit geringer Wahrscheinlichkeit einen Schnitt herstellen kann, der genau den tiefsten Punkt der Läsion zeigt. Bei der Beurteilung der Läsionstiefe durch µCT hingegen kann in den Schnittbildern der tiefste Punkt der Läsion bestimmt werden und die Proben können anschließend noch weiter untersucht werden.

Im klinischen Alltag wird das von der DIAGNOcam durch die Lichtleiter emittierte kohärente Laserlicht zunächst durch Gingiva und Alveolarknochen geleitet, bevor es auf die Zahnwurzel trifft. Es kommt dadurch bereits im Gewebe zu Umwandlungseffekten wie Reflexion, Brechung oder Beugung, die das kohärente Licht streuen, sodass es in inkohärentes Licht umgewandelt wird. Wenn nun das kohärente Laserlicht der DIAGNOcam in-vitro direkt auf die optisch rauen Wurzeln von extrahierten Zähnen trifft, kommt es zu einer starken Bildung von Specklemustern. Diese Interferenzphänomene erschweren die Beurteilung der Approximalflächen. Es ist daher notwendig, das Laserlicht in in-vitro-Versuchen zu streuen, bevor es auf die Zahnwurzel trifft. Dafür gibt es verschiedene Methoden. Eine effektive Strategie zu

Speckle Reduktion ist das Einsetzen von beweglichen oder rotierenden Diffusoren in den Strahl, oder kleine Bewegungen des beleuchteten Objektes (Shin et al., 2006). Eine Alternative dazu ist die Verwendung von kolloidalen Dispersionen durch die das Licht geleitet wird bevor es auf das Objekt trifft, was den Vorteil hat, dass keine mechanischen Bewegungen irgendeiner Komponente erforderlich sind (Riechert, Bastian, & Lemmer, 2009). Die Teilchen oder Tröpfchen der dispersen Phase im Dispersionsmedium unterliegen der brownschen Bewegung. Dies bedeutet, dass sich mikroskopisch sichtbare Teilchen in Gasen oder Flüssigkeiten aufgrund von Wärme ungeordnet bewegen (Brown, 1828). An diesen bewegten Teilchen kann das kohärente Laserlicht beim Durchtritt durch die kolloidale Dispersion so gestreut werden, dass keine Specklemuster mehr wahrnehmbar sind. Lässt man also bei der Nahinfrarot-Transillumination das Laserlicht bevor es auf die Zahnwurzel trifft ein Kolloid passieren, können Specklemuster reduziert werden. Dies entspricht den Umwandlungseffekten des Gewebes. Außer einem Intensitätsverlust des Lichtes durch Reflexion, Brechung oder Beugung an der dispersen Phase gibt es keine negativen Auswirkungen auf die resultierende Bildqualität.

Eine weitere Herausforderung bei der Nahinfrarot-Transillumination sind über- oder unterbelichtete Bildbereiche. Diese können beispielsweise durch Lichtquellen in der Umgebung, metallische Restaurationen im Bildausschnitt oder direkte Lichteinstrahlung in die Kamera aufgrund mangelhafter Adaption der Lichtleiter an die Gingiva verursacht werden. Dieser hohe Dynamikumfang durch die Helligkeitsunterschiede kann in seiner Gesamtheit nicht von einem normalen CMOS Sensor erfasst werden. Eine Möglichkeit um Szenen dennoch mit einem hohen Dynamikumfang aufzuzeichnen und Details auch in sehr hellen oder dunklen Bereichen darzustellen sind Hochkontrastbilder, auch HDRI (High Dynamic Range Image) genannt. Während ein CMOS Sensor immer nur einen begrenzten Dynamikumfang erfassen kann, so lässt sich doch durch mehrfache Änderung der Belichtungseinstellungen der gesamte Dynamikumfang einer Szene erfassen. Dabei entsteht eine Belichtungsreihe, deren einzelne Bilder anschließend durch gewichtete Mittelwertbildung zu einem einzelnen HDR-Bild kombiniert werden können (Mann & Picard, 1995; Mantiuk, 1999). Dieses Verfahren wird in der professionellen Fotografie verwendet und findet auch beispielsweise in der Architektur Anwendung. Dort wird es genutzt um den Informationsverlust durch über- oder unterbelichtete Pixel in Bildern, die für 3D Rekonstruktionen verwendet werden sollen, zu verringern (Kontogianni, Stathopoulou, Georgopoulos, & Doulamis, 2015). Somit könnte die Kombination aus Nahinfrarot-Transillumination und Hochkontrastbildern die Kariesdiagnostik durch bessere Detaildarstellung und höheren Dynamikumfang gegenüber der konventionellen Nahinfrarot-Transillumination erleichtern.

Neben der Bildqualität kann die zuverlässige Interpretation von Röntgenbildern und Nahinfrarot-Transilluminations-Aufnahmen durch verschiedene Verzerrungen bzw. Bias beeinflusst werden. Zunächst benötigt es eine eindeutige Klassifikation, um Befunde und Diagnosen behandlerunabhängig stellen zu können. Von Söchtig et al. wurde 2014 eine Klassifizierung nach Läsionstiefe vorgestellt (Söchtig et al., 2014). Diese soll eindeutige und objektive Diagnosen erleichtern. Der Interpretationsspielraum sowie die Eindeutigkeit einer Klassifikation lässt sich überprüfen, in dem man verschiedene Untersucher gleiche Fälle untersuchen lässt und anschließend Interrater- und Intrarater-Reliabilität bestimmt. So zeigt sich, ob die Untersucher bei wiederholter Bewertung mit sich selbst oder aber mit anderen Untersuchern übereinstimmen. Doch trotz Verwendung einer eindeutigen Klassifikation können Voreingenommenheiten aufseiten des Behandlers nicht ausgeschlossen werden. Mögliche Einflüsse sind beispielsweise Ausbildung und Erfahrung des Untersuchers, die Umgebung, in der die Interpretation erfolgt, und das Wissen des Untersuchers über die klinische Situation. Daher ist es notwendig, potenzielle Quellen von Verzerrungen zu untersuchen, um zuverlässige Diagnosen und Studienergebnisse zu erzielen.

Zur Bestimmung der Interrater- und Intrarater-Reliabilität eignet sich beispielsweise die Kappa Statistik von Cohen (Cohen, 1960). Damit kann das allgemeine Maß der Übereinstimmung unter Rücksichtnahme auf die zufällig zu erwartende Übereinstimmung bestimmt werden. Da es sich bei der Klassifikation um eine Ordinalskala handelt, sind manche Differenzen zwischen Untersuchern schwerwiegender als andere. Dafür kann das gewichtete Kappa verwendet werden.

Ziele dieser Arbeit

In bisherigen Studien, die das Problem des Speckle erkannt haben, wurde zur Verhinderung von Specklemustern auf inkohärente Lichtquellen wie Wolfram-Halogenglühlampen oder Superlumineszenzdioden zurückgegriffen (Daniel Fried, Staninec, & Darling, 2010; J. C. Simon et al., 2016; Jacob C. Simon et al., 2014). Ziel der ersten Studie war die Entwicklung eines In-vitro-Modells zur Validierung von Nahinfrarot-Transillumination für die proximale Kariesdetektion, welches Specklemuster auch bei der Verwendung von konventionellen Laserdioden aus Geräten wie der DIAGNOcam reduziert. Zusätzlich sollte die Nahinfrarot-Transillumination mit der HDR-Bildgebung ergänzt (NIRT-HDRI) und mit der konventionellen Nahinfrarot-Transillumination verglichen werden. Beide Methoden sollten dafür aufgrund der Vorteile mit µCT validiert werden und Sensitivität und Spezifität bestimmt werden.

Um die Objektivität der Nahinfrarot-Transillumination zu bestimmen, wurden in der zweiten Studie die Interrater- und Intrarater-Reliabilität untersucht und mit der Röntgendiagnostik verglichen. Anschließend wurde der Einfluss verschiedener Faktoren wie Erfahrung eines Arztes oder Untersuchungszyklus auf die Übereinstimmung mittels logistischer Regressionsanalyse bestimmt.

Deutsche Zusammenfassung

Ziel der ersten Studie war die Entwicklung eines In-vitro-Modells zur Validierung der Nahinfrarot-Transillumination mit DIAGNOcam für die proximale Kariesdetektion. Um Specklemuster zu reduzieren, wurden in Vorversuchen verschiedene Kolloide zur Streuung des kohärenten Laserlichts getestet. Dabei schnitt homogenisierte Milch mit einem Fettgehalt von 4 % deutlich besser ab als beispielsweise verschiedene Verdünnungen von Hydroxylapatit-Suspensionen. Zur Transillumination wurden zwei 780-nm-Laserdioden der Klasse 1 von KaVo verwendet, die auch im Handstück der DIAGNOcam verbaut sind. Daran wurden Lichtleiter gekoppelt, die das Licht durch zwei kleine Löcher in eine mit Milch gefüllte Küvette leiteten. Der originale DIAGNOcam Ansatz mit den flexiblen Lichtleitern wurde nicht verwendet, da er nicht über die Küvette passte. Die Küvette wurde mit einem lichtundurchlässigen Deckel bedeckt mit einer mittigen Aussparung für die Zahnwurzeln der zu untersuchenden Zähne. Anschließend wurden mit der DIAGNOcam und der zugehörigen Software Bilder von beiden Approximalflächen von 53 Zähnen aufgenommen.

Des Weiteren sollte überprüft werden, ob die Ergänzung der Nahinfrarot-Transillumination mit der HDR-Bildgebung Vorteile für die Diagnostik bringt. Dazu wurden von den Zähnen zusätzlich zu den DIAGNOcam Aufnahmen Belichtungsreihen mit einer Nah-Infrarot-Kamera erstellt. Die Belichtungszeiten variierten von 9 ms bis 57 ms, von jedem Zahn wurden Bilder mit 13 unterschiedlichen Belichtungen aufgenommen. Für jedes Bild wurde ein Gewichtungsfaktor berechnet, für den die Belichtungszeit des einzelnen Bildes durch die maximale Belichtungszeit von 57 ms dividiert wurde. Anschließend wurde aus den einzelnen Bildern unter Verwendung des Gewichtungsfaktors ein HDR-Bild berechnet.

Alle durch beide Untersuchungsmethoden erfassten Bilder wurden in zwei Untersuchungszyklen von zwei Untersuchern bewertet und mit Mikro-Computertomografie-Schnittbildern verglichen. Bei der statistischen Auswertung zeigten beide Untersuchungsmethoden nahezu perfekte Interrater- und Intrarater-Reliabilität. Die Gesamtübereinstimmung zwischen DIAGNOcam und NIRT-HDRI (gewichtetes Kappa) war nahezu perfekt (0,85). In der Kategorie 4 war die

Übereinstimmung (Kappa) zwischen den DIAGNOcam und NIRT-HDRI sehr hoch (0,88), in den Kategorien 0 und 3 etwas niedriger (0,8 und 0,67). Am niedrigsten war die Übereinstimmung in den Kategorien 1 und 2 (0,59 und 0,43).

Zur Validierung mit Mikro-Computertomografie wurde zwischen gesunden Oberflächen, Schmelzkaries und Dentinkaries unterschieden. Anschließend konnten Sensitivität und Spezifität berechnet werden. Die Werte lagen zwischen 0,57 und 0,99 und waren in den verschiedenen Kategorien für beide Untersuchungsmethoden ähnlich. NIRT-HDRI hatte eine höhere Sensitivität für gesunde Oberflächen und Schmelzkaries sowie eine höhere Spezifität für Dentinkaries.

Die erzeugten NIRT-HDR-Bilder zeigten einen deutlich höheren Dynamikumfang als die herkömmlichen NIRT-Bilder der DIAGNOcam was zu einer detaillierteren Visualisierung von Strukturen führte. Unter- und überbelichtete Bereiche konnten reduziert und Karies in den meisten Fällen deutlicher differenziert werden. Allerdings verbesserte sich die Diagnostik dadurch nicht signifikant. Die Unterscheidung zwischen fortgeschrittenen Schmelzläsionen und Dentinläsionen scheint ein spezifisches Problem für NIRT zu sein, da aufgrund der optischen Eigenschaften von Dentin Läsionen im Dentin oftmals nicht sichtbar sind.

In der zweiten Studie wurde die Interrater- und Intrarater-Reliabilität von insgesamt 12 Untersuchern bei der Bewertung von digitalen Bissflügelröntgenaufnahmen und DIAGNOcam Aufnahmen untersucht sowie der Einfluss der Untersuchungsmethoden, des Evaluationszyklus, der Erfahrung der Untersucher und des Zahntyps auf die Diagnostik. Dazu wurden 211 Bildpaare zunächst von zwei Untersuchern unabhängig voneinander beurteilt, die sich anschließend auf eine Konsensdiagnose einigten. Aus diesen Bildpaaren wurden 100 Paare von insgesamt 85 Patienten, für die weiteren Untersuchungen verwendet, die sich zu ca. je einem Drittel aus gesunden Flächen, Schmelz- und Dentinläsionen zusammensetzten. Diese wurden von 12 Zahnärzten mit unterschiedlicher klinischen Erfahrung nach einem theoretischen und praktischen Training in zwei Zyklen mit einem vierwöchigen Abstand analysiert.

Die statistische Analyse ergab in den meisten Fällen eine Abweichung zu der Konsensdiagnose um maximal eine Kategorie. Analysen aller Interexaminer-Werte des ersten Evaluierungszyklus zeigten, dass 69,8% der Bissflügel-Röntgenbilder und 79,0%

der NIRT-Bilder richtig bewertet wurden. Der zweite Evaluationszyklus ergab 72,4% konkordante Diagnosen bei den Bissflügelröntgenaufnahmen und 71,2% bei den DIAGNOcam-Aufnahmen. Auch die Kappa-Statistik zeigte eine leichte Zunahme der Interrater-Reliabilität der Röntgendiagnostik mit einer leichten Abnahme bei den DIAGNOcam Diagnosen im zweiten Zyklus.

Die Binär-Logistische-Regressionsanalyse zeigte bei DIAGNOcam und Röntgendiagnostik einen signifikanten Einfluss der Untersuchungsmethoden und des Untersuchungszyklus auf die Reliabilität der Diagnosen. DIAGNOcam Bilder wurden im ersten Zyklus mit einer höheren Wahrscheinlichkeit richtig diagnostiziert als im zweiten. Hingegen zeigten die klinische Erfahrung oder der Zahntyp keinen signifikanten Einfluss.

Englische Zusammenfassung

The purpose of the first study was the development of an in-vitro model for the validation of near-infrared transillumination (NIRT) with DIAGNOcam for proximal caries detection. To scatter the coherent laser light and to reduce speckle patterns, various colloids were tested in preliminary experiments. Homogenized milk with a fat content of 4% performed significantly better than, for example, various dilutions of a hydroxyapatite solution. Two 780 nm class 1 laser diodes from KaVo were used for transillumination, which are identical to the diodes installed in the handpiece of DIAGNOcam. Optical fibers were coupled to the diodes, directing the light through two small holes in a milk-filled cuvette. The original clinical tip of DIAGNOcam with the flexible light guides was not used because it did not fit over the cuvette. The cuvette was covered with an opaque lid with a central recess for the root of the tooth to be examined. Subsequently, images of both proximal surfaces of 53 teeth were recorded with DIAGNOcam and the associated software.

Besides validating DIAGNOcam, the aim was to investigate whether the combination of near infrared transillumination with HDR imaging offers diagnostic advantages. Therefore, in addition to the DIAGNOcam recordings, exposure series of all teeth were shot using a near-infrared camera. Exposure times varied from 9ms to 57ms, images with 13 different exposures were taken of each tooth. For each image, a weighting factor was calculated, dividing the exposure time of each image by the maximum exposure time of 57ms. Subsequently, an HDR image was calculated from the individual images using the weighting factors.

All images captured by both methods were scored by two investigators in two cycles and compared to micro-CT scans. In the statistical analysis, both methods showed nearly perfect inter- and intra-rater reliability (weighted kappa). The overall agreement between DIAGNOcam and NIRT-HDRI (weighted kappa) was almost perfect (0.85). In category 4, agreement (simple kappa) between DIAGNOcam and NIRT-HDRI was very high (0.88), in categories 0 and 3 slightly lower (0.8 and 0.67). The lowest kappa was calculated for categories 1 and 2 (0.59 and 0.43).

For validation with micro computed tomography a distinction was made between healthy surfaces, surfaces with enamel lesions and surfaces with dentin lesions. Subsequently, sensitivity and specificity could be calculated. Values ranged from 0.57 to 0.99 and were for both methods similar in the different categories. NIRT-HDRI had a higher sensitivity for healthy surfaces and enamel caries as well as a higher specificity for dental caries.

The generated NIRT-HDR images showed a significantly higher dynamic range than the conventional NIRT images of the DIAGNOcam, resulting in a more detailed visualization of structures. Under- and overexposed areas could be reduced and caries differentiated more clearly in most cases. However, sensitivity or specificity did not improve significantly. The distinction between advanced enamel lesions and dentin lesions appears to be a specific problem for NIRT, as lesions in dentin are often not visible due to the optical properties of dentine.

The second study evaluated the inter- and intra-rater reliability of 12 examiners in assessing digital bitewing radiographs and DIAGNOcam images, as well as the influence of the examination method, evaluation cycle, experience of the examiner and the tooth type on the diagnosis. Therefore, a total of 211 image pairs were first assessed independently by two examiners who subsequently agreed on a consensus diagnosis. From these, 100 pairs of 85 patients, consisting of approximately one third of healthy surfaces, enamel lesions and dentin lesions, were used for the further examinations. All image pairs were analyzed by 12 dentists with different clinical experience after a theoretical and practical training in two cycles with a four-week interval.

The statistical analysis revealed in most cases a deviation by a maximum of one category from the consensus diagnosis. Analyzes of all inter-examiner values from the first evaluation cycle showed that 69.8% of the digital bitewing images and 79.0% of the NIRT images were correctly assessed. The second cycle of evaluation revealed 72.4% concordant diagnoses in bitewing radiographs and 71.2% in DIAGNOcam images. Kappa statistics also showed a slightly increased inter-rater reliability of X-ray diagnostics in the second evaluation cycle, but a decrease in DIAGNOcam.

Binary-logistic regression analysis showed a significant influence of the examination cycle and of the diagnostic method on the reliability of the diagnosis. DIAGNOcam images were more correctly diagnosed in the first cycle than in the second cycle. On the other hand, the clinical experience or the tooth type did not show any significant influence.

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Transillumination and HDRI for proximal caries detection

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Abstract

The purpose of this study was to develop an in vitro model for the validation of near-infrared transillumination (NIRT) for proximal caries detection, to enhance NIRT with high-dynamic-range imaging (HDRI), and to compare both methods, using micro-computed tomography (µCT) as a reference standard. Both proximal surfaces of 53 healthy or decayed permanent human teeth were examined using the Diagnocam (DC) (KaVo) and NIRT with HDRI (NIRT-HDRI). NIRT was combined with HDRI to improve the diagnostic performance by reducing under- and overexposed image areas. For NIRT-HDRI, an exposure series was captured and merged into a single HDR image. A classification was applied according to lesion depth. All surfaces were assessed twice by 2 trained examiners, and additionally with µCT for validation. The Kappa statistic was used to calculate inter-rater reliability and agreement between DC and NIRT-HDRI. Inter-rater reliability (weighted Kappa, wκ) showed very good agreement for the DC (0.90) and NIRT-HDRI (0.96). The overall agreement (wκ) was almost perfect (0.85). In the individual categories (0 to 4), the agreement (simple Kappa) ranged from almost perfect (category 4) to moderate (1 and 2) to substantial (categories 0 and 3). Sensitivity and specificity of sound surfaces, enamel, and dentin caries ranged from 0.57 to 0.99 and were similar for both methods in the different categories. NIRT-HDRI had a higher sensitivity for sound surfaces and enamel caries, as well as a higher specificity for dentin caries. Regarding the obtained images, HDRI allowed for the detection of caries within a greater range of luminance levels, resulting in a more detailed visualization of structures without under- or overexposure. However, HDRI

this did not improve the diagnostics significantly. Distinguishing between a processed demineralized enamel and dentin lesions appears to be a problem specific to NIRT and cannot be balanced using HDRI.

Introduction

The detection of proximal caries at an early stage is a major challenge. Visual-tactile and radiographic examination have their limitations and are insufficient for the detection of incipient proximal lesions in many cases. Visual assessment is difficult in the interdental space and the prevalence of proximal lesions are therefore underestimated (Poorterman et al. 1999; Poorterman et al. 2002). Radiographs often show overlapping effects and artifacts, and their sensitivity for the detection of enamel caries is moderate (Abesi et al. 2012). Furthermore, repeating radiographs is restricted because of ionizing radiation. Therefore, additional diagnostic methods of sufficient diagnostic accuracy are needed for the early detection of proximal lesions (Hume 1993; Featherstone 1999; National Institutes of Health 2001).

Diaphanoscopy has been applied in different fields of general medicine for many years, even before the discovery of X-rays (Kierzek 1995; Shurtleff et al. 1966). In dentistry, transillumination is also a highly promising method for caries detection. Following the development of fiber optics using visible light, the focus has shifted toward the use of near-infrared (NIR) light for the transillumination of teeth (Bussaneli et al. 2015; Kachalia 2015; Simon et al. 2015; Kühnisch et al. 2016; Simon et al. 2016).

Sound enamel is highly transparent when imaged in the infrared range. As such, irregularities, such as demineralization, can be visualized with high contrast (Jones et al. 2003; Fried et al. 2005). Several diagnostic tools using NIR light—for example, the Diagnocam (DC) (KaVo) or the VistaCam (Dürr Dental)—have been introduced to the dental market over the past 5 y.

Various clinical studies have discussed and assessed the utility of DC (Abdelaziz and Krejci 2015; Abdelaziz et al. 2016; Kühnisch et al. 2016). Two NIR laser diodes (with a power of 1 mW and a wavelength of 780 nm) transilluminate molars and premolars from the buccal and lingual sides through the gingiva, alveolar process, and dental roots up to the crown. A monochrome complementary metal-oxide-semiconductor (CMOS) sensor captures the images from the occlusal direction with an image angle of 105°. Live images can be visualized and captured on a computer.

Several in vivo studies have suggested the potential of this technique for the detection of proximal caries, suggesting comparable or even superior clinical performance over digital bitewing radiographs. However, in clinical use, DC images often have under- and overexposed areas. This may be a result of intense light sources in the environment that cause reflections, metallic restorations in the examined area, or direct laser light into the camera due to a lack of adaptation. Hypo- or hypermineralization, or the morphology of the occlusal surface can also have an effect. In cases where the brightness difference in a picture from light to dark areas is higher than the camera sensor can display, high-dynamic-range imaging (HDRI) can be useful. Differently exposed images are needed to calculate a HDR image, allowing for a greater range of luminance levels and evenly exposed, sharper and more detailed images. The combination of NIR transillumination (NIRT) with HDRI may offer an avenue to improve NIRT image quality.

DC has been used in several in vitro studies (Marinova-Takorova et al., 2014; Abdelaziz et al., 2016; Abogazalah et al., 2017). However, our in vitro model differs significantly from those previously presented. When coherent laser light is directly applied on extracted teeth, speckle patterns are produced, causing poor image quality. At present, there is no solution to reduce the speckle phenomenon or under- and overexposed image areas; this is emphasized in the development of our in vitro model.

The purpose of this in vitro study was to develop an in vitro model for the validation of NIRT for proximal caries detection, to enhance NIRT with HDRI (NIRT-HDRI), and to compare both methods using micro-computed tomography (µCT) as a reference standard.

Materials and Methods

Sample Selection

Fifty-three freshly extracted healthy or decayed permanent human teeth with fully formed apices were selected by 2 examiners (A.L. and F.L.). The specimens showed either an intact, sound interproximal surface or non-cavitated proximal caries lesions. An equal number of intact and visibly changed proximal surfaces was obtained. Teeth with metallic restorations, secondary caries, residual caries or damage due to the extraction process were excluded from this study. The selected teeth were cleaned with an acoustic scaler to remove plaque, calculus, and debris, and stored in distilled water at 4°C. Age, sex, and race of the patients were unknown. All experimental procedures were approved by the Ethics Committee of the Medical Faculty, Ludwig Maximilians University in Munich, Germany (488-15 UE).

Examination by NIRT

An in vitro model was developed to simulate the working principle of the DC in clinical use (Figure 1). NIR light is transmitted through a diffusely scattering liquid and guided through the root to the crown.

Light scattering by particles in a colloid is known as the Tyndall effect. Different liquids were tested for diffusing and scattering light, including solutions with hydroxyapatite or milk. The best results were obtained using homogenized milk with a 4% fat content.

A round cuvette with a spill tray was mounted on a vertical and horizontal translation stage with micrometers for fine positioning. Two fiber-optic light guides were inserted through small holes 2 mm under the rim and subsequently sealed with boxing wax (Kerr). The light guides were connected to a laser optical unit with a 780-nm class 1 laser diode in a housing (KaVo), which is the same laser integrated in the DC. The laser was operated by a 5 V and 50 mA laboratory power supply (VLP-1303 PRO, VOLTCRAFT). The cuvette was filled with milk and covered with a 30 × 30 mm boxing wax strip with adhered black opaque tape on top to block direct light. A small 10 × 10 mm square was cut in the middle, and the resulting recess was covered by self-adhesive foam sealing tape with a small hole in the middle for the teeth. As all

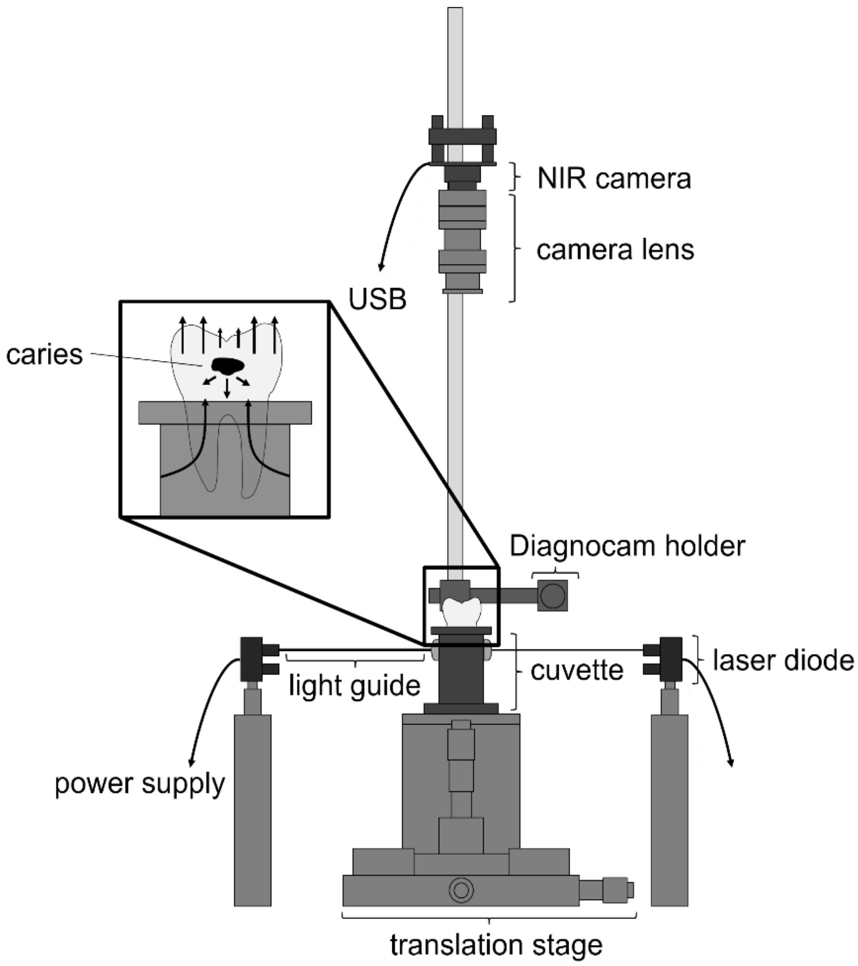


Figure 1. Schematic illustration of the near-infrared transillumination setup.

investigations were conducted in a darkened room, the only light that could reach the camera was light guided through the root to the crown of the tooth. This was done to standardize the examination and prevent reflections on the tooth surface by ambient light. Images were obtained with an above-mounted NIR camera manufactured by IDS (UI-1241LE-NIR-GL, Imaging Development Systems GmbH) together with a Tamron 50-mm lens (M118FM50, TAMRON Europe GmbH).

In addition, a horizontal arm with a mounting bracket for the DC was attached, so that the DC and the experimental camera could evaluate the same tooth under similar conditions. Instead of the clinical tip of the DC, the laser optical unit of the in vitro model was used for transillumination to obtain comparable images. The DC could be pivoted over the tooth, and images obtained with the KaVo KiD (KaVo integrated Desktop) software. Subsequently, an exposure series was shot with the NIR camera with a 4-ms interval between consecutive shots. Images were evenly exposed at 33 ms. Six further over- and underexposed images were taken for an even graduation. The exposure series started at 9 ms and ended at 57 ms; therefore, a total of 13 images of each tooth were taken. Images with exposure times under 9 ms or over 57 ms were not suitable for HDR rendering.

The obtained image sets were further processed with Fiji (Schindelin et al. 2012), a distribution of ImageJ. A weighting factor was calculated for each image (exposure time of the individual image divided by the maximum exposure time of 57 ms), and all images merged into a single HDR image using the "KHKsBwHdrCalculatorExt" Plugin for Fiji (K.H.K).

Examiners

Before assessing the images, two experienced examiners (A.L. and F.L.) were given a practical and theoretical training session. Then, all images were analyzed and described using a modified diagnostic classification for NIRT images, describing different stages of proximal caries (0 to 4) (Figure 2) (Söchtig et al. 2014). The assessment of the images was conducted independently by both examiners on a calibrated standard monitor (Windows "Display Color Calibration" wizard) in a darkened room to standardize image evaluation. This was repeated with a minimum interval of 2 wk to prevent misclassification and to calculate the inter- and intra-rater reliability.

Validation with Micro-Computed Tomography

Each tooth was mounted vertically and separately in a water-filled cuvette, which was sealed with Parafilm M (Bemis Company) to stop the samples drying out. The coronal and upper part of the root were scanned using a µCT40 fully shielded, cone-beam, desktop micro-CT scanner (Scanco Medical) at 70 kV and 114 µA, with a field of view limited to 16.5 mm. The resulting pixel size in the obtained raw data sets (RSQ files) was equal to 0.032 mm. The RSQ files were reconstructed into 3D data sets (ISQ files) and further processed with Fiji (Schindelin et al. 2012) and the plugin "Import ISQ"

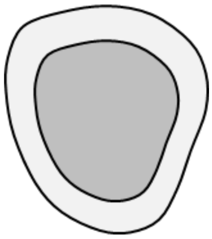
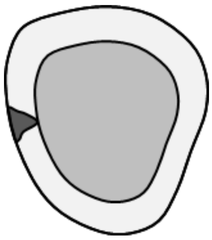
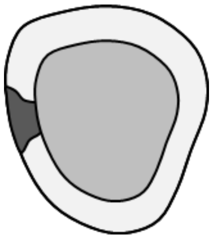
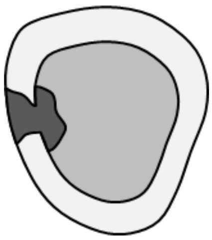
Index	Description	Example
0	No tooth decay	
1	Caries visible in enamel	
2	Caries visible in enamel with single-point contact to the dentino-enamel junction	
3	Caries visible in enamel with extensive contact to the dentino-enamel junction	
4	Caries visible in enamel and dentin	

Figure 2. Disease severity scale for use with near-infrared transillumination images.

(K.H.K). Measurements of the horizontal spread of the caries, caries width at the dentino-enamel junction, and enamel thickness were taken. Measurements were taken 3 times by one examiner, and the mean values calculated. The surfaces were then classified using the following criteria: absence of radiolucency (0), radiolucency in the outer (E1), or the inner half of the enamel (E2), and radiolucency in the dentin (D).

Statistical Analyses

A crosstabulation was used to compare the DC and NIRT-HDRI diagnoses with µCT scores and shows the distribution. The linearly weighted Cohen's Kappa (wκ) coefficient was used to measure the inter- and intra-rater reliability for both diagnostic methods and to determine the overall agreement between the DC and NIRT-HDRI results. Agreement values between the DC and NIRT-HDRI assessment per category were calculated using the simple Kappa statistic (κ). To compare µCT, DC and NIRT-HDRI on an equivalent basis, a distinction was made for sound surfaces, enamel caries, and dentin caries. For each of these categories sensitivity and specificity were calculated. Data were analyzed using SPSS 23 (SPSS Inc.) and MedCalc Statistical Software 17.5.5 (MedCalc Software bvba).

Results

Linear wκ values for inter-rater agreement showed almost perfect agreement for both diagnostic modalities: 0.9 for the DC and 0.96 for NIRT-HDRI (Landis and Koch 1977). The same applies for intra-rater agreement (A.L. and F.L.): 0.96 and 0.91 for the DC, for NIRT-HDRI 0.9 and 0.93.

A cross-tabulation (Table 1) presents the distribution of diagnoses. High consistency was noted between DC and NIRT-HDRI diagnoses. A maximum discrepancy of one category was observed for almost all categories. Whereas only a few surfaces were classified by DC and NIRT-HDRI as category 4 (directly associated with dentin caries), many more surfaces were classified as category 4 by µCT.

The agreement values (κ) between the DC and NIRT-HDRI diagnoses were almost perfect in category 4 (0.88) and were substantial in categories 0 and 3 (0.8 and 0.67). In categories 1 and 2, the agreement was moderate (0.59 and 0.43). The overall agreement (wκ) was almost perfect (0.85; 0.95 confidence interval of 0.78 to 0.92).

		Diagnocam					NIRT-HDRI					
		0	1	2	3	4	0	1	2	3	4	Total
µCT	0	64	3	1	0	0	65	3	0	0	0	68
	1	4	6	0	1	0	4	6	1	0	0	11
	2	3	3	3	1	0	3	2	4	1	0	10
	3	1	1	1	10	4	1	1	3	7	5	17
	Total	72	13	5	12	4	73	12	8	8	5	106

Table 1. Cross-table of Diagnocam and Near-Infrared Transillumination High-Dynamic-Range Imaging (NIRT-HDRI) in Comparison with µCT Diagnoses.

Thresholds were defined for sound surfaces, enamel caries, and dentin caries. DC or NIRT-HDRI category 0 was classified as sound, category 1 and 2 as enamel caries. The comparison of DC and NIRT-HDRI with µCT (Table 1) showed that most surfaces classified as category 3 had dentin lesions; therefore, category 3 was chosen as the threshold for dentin caries. Next, we calculated the sensitivity and specificity for sound surfaces, enamel caries, and dentin caries (Table 2). The values ranged from 0.57 to 0.99 and were similar for both methods in the different categories. NIRT-HDRI had a higher sensitivity for sound surfaces and enamel caries as well as a higher specificity for dentin caries. The lowest sensitivity was calculated for enamel lesions, 0.57 for DC and 0.62 for NIRT-HDRI; however, the specificity was high.

		Sensitivity	Specificity
Diagnocam	Sound	0.94	0.79
	Enamel	0.57	0.93
	Dentin	0.82	0.98
NIRT-HDRI	Sound	0.96	0.79
	Enamel	0.62	0.92
	Dentin	0.71	0.99

Table 2. Sensitivity and Specificity of the Diagnocam and Near-Infrared Transillumination High-Dynamic-Range Imaging (NIRT-HDRI) using Micro-Computed Tomography as Reference Standard.

The generated NIRT-HDR images show more details and brightness gradations in shadows and light than conventional NIRT images (Figure 3). Under- and overexposed areas could be reduced, and caries differentiated more clearly in most cases.

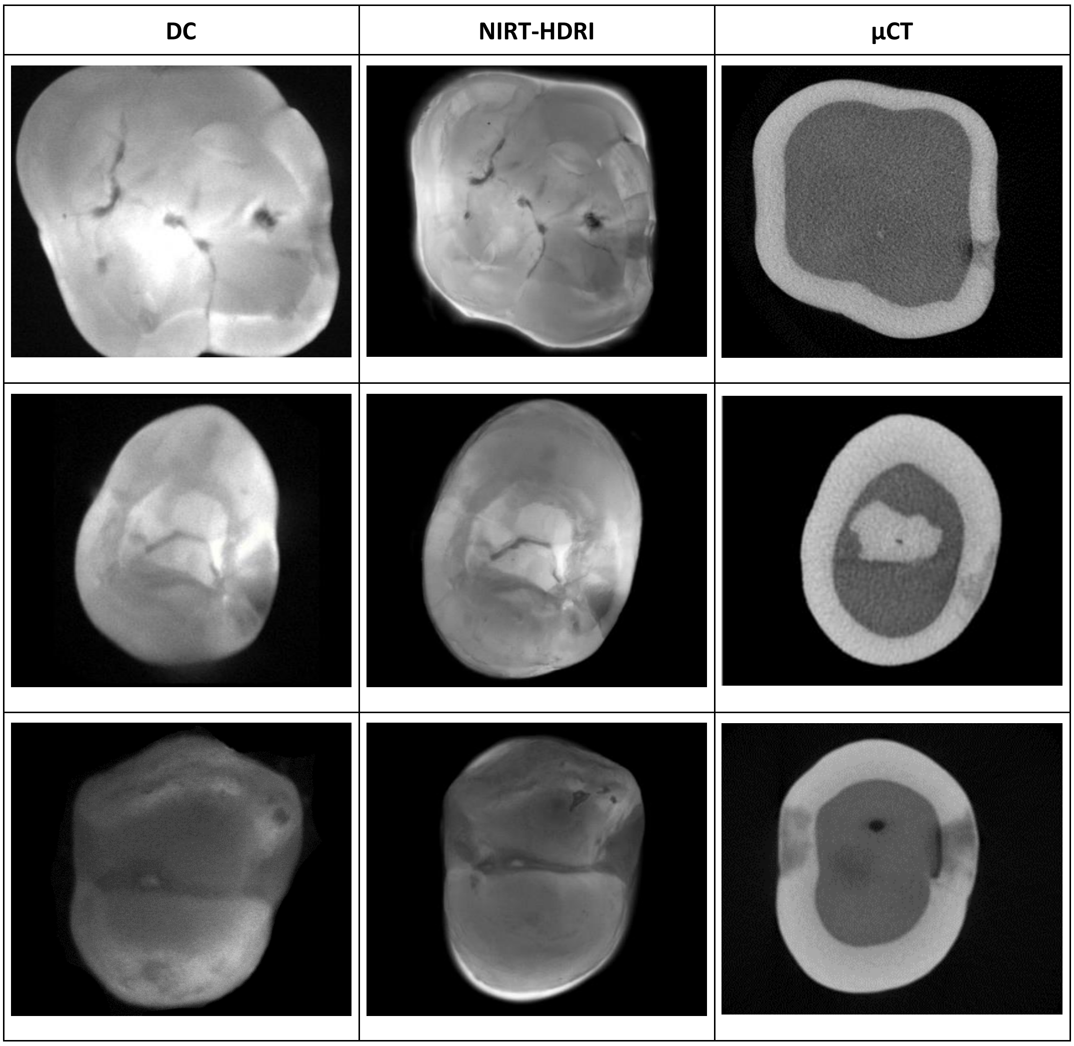


Figure 3. Sensitivity and Specificity of the Diagnocam and Near-Infrared Transillumination High-Dynamic-Range Imaging (NIRT-HDRI) using Micro-Computed Tomography as Reference Standard.

Discussion

The early detection of incipient proximal caries lesions is of increasing importance because, at present, these initial lesions can be treated by non- and micro-invasive methods to prevent their progression onto stages where it is necessary to “drill and fill” (Dorri et al. 2015). Visual inspection and radiographic examinations often underestimate proximal caries lesions (Bader et al. 2001; Selwitz et al. 2007); for this reason, alternatives, such as transillumination, need to be investigated and validated.

This study evaluated the suitability of NIRT combined with HDRI for the detection of proximal caries lesions. The project focused on the in vitro comparison of proximal caries diagnostics with the DC and NIRT-HDRI using µCT as reference standard. It was not possible for us to obtain a satisfactory image quality when using the DC with the clinical tip in vitro without scattering the laser light. This resulted in overexposed image areas and speckle phenomena. With a light diffusing liquid, we could simulate the scattering properties of the tissue surrounding the tooth. To generate comparable images with both diagnostic methods, the original DC lasers from KaVo were used as a common light source for both methods. Although this differs to that used in the clinic, it was necessary for our in vitro model.

In dentin, the scattering coefficient showed minimal decreases with the increasing wavelength but was very low in enamel in the NIR range (Kienle et al. 2006; Moritz 2006). This implies an increasing penetration depth of light, which is needed for transillumination (Fried et al. 2005). The optimal wavelength for NIRT is between 795 nm and ~1,600 nm (Darling et al. 2006). Transilluminating teeth for caries detection in this range was patented in 2006; therefore, manufacturers have used slightly lower wavelengths for their products (for example, 780 nm).

The correlation of DC and NIRT-HDRI diagnoses showed a strong agreement for categories 0 and 4, representing sound teeth and dentin caries (κ 0.80 and 0.88), whereas other categories showed less agreement. These differences in diagnoses may have been caused by several factors. First, the µCT validation showed that the selected samples contained more sound than decayed surfaces; at least, the demineralization in these samples were superficial and not detectable with any of the methods used. Therefore, discordant diagnostic decisions did not have a strong effect in category 0. Furthermore, the diagnosis “sound” is usually a clear decision for examiners (Bader et al. 2001), whereas other categories are more subjective, requiring interpretation and judgment, especially to allocate between borderline cases; for example, when deciding whether a carious lesion has single-point contact to the dentino-enamel junction (category 2) or is located immediately before the junction (category 1).

Categories 1 and 2 showed low agreement values in our study (κ 0.59 and 0.43). In addition, categorization may be influenced in some cases by the camera angle. It may be worth combining categories 1 and 2 in future studies. However, it must first be examined whether it makes sense to combine these categories or whether another classification system should be established. Taken together, this information might explain the moderate Kappa values for both categories and highlights a universal problem in the visual classification of borderline cases using systems as compared to continuous scales.

In radiography, the pulp serves as a reference to evaluate lesion depth; this is not possible with NIRT due to the superposition of scattering by mineral crystals, collagen fibrils, and dentinal tubules in dentin (Zijp and ten Bosch 1993). Likewise, caries in dentin can only be shown in some cases. Different dentin lesions with similar extension in X-ray images are not always visible in NIRT images because of visibility. We suggest that clear visualization of dentin caries (category 4) is only possible if the lesion is located directly under the occlusal enamel layer. More cervically-located dentin lesions—with healthy dentin between the lesion and occlusal enamel—cannot be visualized. In addition, the extension of the caries and the degree of demineralization affect visualization. Where there is high contrast between the demineralization and the sound enamel, it is possible to indirectly extrapolate a dentin lesion from caries visible in the enamel with extensive contact to the dentino-enamel junction (Kühnisch et al. 2016). These findings should be verified histologically or by computer tomography in further studies.

In our study, we preferred µCT as a reference standard, as it offers several advantages. Without destroying the samples, even small structural changes can be visualized. By taking scans of the entire sample, we can determine where the lesion is most advanced. µCT has been used in other studies for examination and validation (Matsuda 2002; Shahmoradi and Swain 2017), and is reported to perform equal or better than histology for in vitro caries assessment (Soviero et al. 2012; Özkan et al. 2015). Using µCT for validation, we found no major differences in terms of sensitivity or specificity between the 2 methods. The lower sensitivity for enamel caries may be explained by the fact that small enamel demineralization not visible with the

Diagnocam or NIRT-HDRI were detectable in µCT images and thus rated as enamel caries. The threshold chosen for dentin caries, category 3, seems to be appropriate, as sensitivity and specificity are high in this category; as already described above, category 4 is not a suitable threshold for dentin caries.

The combination of NIRT and HDRI allows for a greater range of luminance levels using HDRI. Studies in other disciplines, for example, architecture, have shown the utility of HDRI for identifying detail (Kontogianni et al. 2015). Under- and overexposed image areas can be reduced, especially compared to clinical images. It must be acknowledged, however, that in the present study, NIRT was performed under optimal conditions, and direct light to the camera was blocked. In daily clinical practice, this is usually not possible. In such situations, we would expect HDRI to be superior to simple exposure images. One potential disadvantage of HDRI in clinical use could be blurred images due to the summation of exposure times of the image series and no rigid fixation between the camera and tooth. Possible solutions could be a rigid mechanical support or software-based image stabilization.

To sum up, we successfully developed an in vitro model that is well-suited for validating the Diagnocam and NIRT. Our in vitro study revealed that both methods seem to be well-suited for proximal caries detection. Obtaining images suitable for diagnostics is more difficult on patients than in vitro; therefore, the benefits of HDRI may be more apparent in the clinical setting. This should be evaluated in future studies. Distinguishing between processed demineralized enamel and dentin lesions seems to be a specific problem for NIRT and cannot be balanced using HDRI.

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Inter- and intraexaminer reliability of bitewing radiography and near-infrared light transillumination for proximal caries detection and assessment

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Abstract

Objectives: The purpose of this in vitro study was to evaluate the inter- and intraexaminer reliability of digital bitewing (DBW) radiography and near-infrared light transillumination (NIRT) for proximal caries detection and assessment in posterior teeth.

Methods: From a pool of 85 patients, 100 corresponding pairs of DBW and NIRT images (~1/3 healthy, ~1/3 with enamel caries and ~1/3 with dentin caries) were chosen. 12 dentists with different professional status and clinical experience repeated the evaluation in two blinded cycles. Two experienced dentists provided a reference diagnosis after analysing all images independently. Statistical analysis included the calculation of simple (κ) and weighted Kappa (wκ) values as a measure of reliability. Logistic regression with a backward elimination model was used to investigate the influence of the diagnostic method, evaluation cycle, type of tooth, and clinical experience on reliability.

Results: Altogether, inter- and intraexaminer reliability exhibited good to excellent κ and wκ values for DBW radiography (Inter: κ = 0.60/ 0.63; wκ = 0.74/0.76; Intra: κ = 0.64; wκ = 0.77) and NIRT (Inter: κ = 0.74/0.64; wκ = 0.86/0.82; Intra: κ = 0.68; wκ = 0.84). The backward elimination model revealed NIRT to be significantly more reliable than DBW radiography.

Conclusions: This study revealed a good to excellent inter- and intraexaminer reliability for proximal caries detection using DBW and NIRT images. The logistic regression analysis revealed significantly better reliability for NIRT. Additionally, the first evaluation cycle was more reliable according to the reference diagnoses.

Introduction

Appropriate treatment of dental caries requires valid and reliable methods to detect proximal caries lesions.[1–3] In addition to visual examination, bitewing radiography is the method of choice to date to detect caries lesions on hidden surfaces.[4–6] Near-infrared light transillumination (NIRT) of posterior teeth is a novel non-ionizing imaging method for the detection of proximal caries lesions.[7] The technique combines the application of near-infrared light with digital imaging. Optical properties of demineralized dental tissue differ distinctively from those of the surrounding tissue when longwave light is applied. Sound enamel is highly transparent in the near-infrared portion (700 nm−1 mm) of the electromagnetic spectrum because the attenuation coefficient is lower than in the visible range (400–700 nm).[8] The altered structure of demineralized enamel with larger numbers of pores and interprismatic water accumulation causes increases in light scattering and absorption in these tissues. Therefore, high-contrast visualization of enamel caries lesions is possible using this technique.

Scattering in dentin is a more complex process, as the dentinal tubules behave as Mie scatterers.[9,10] These scatterers describe the scattering of an electromagnetic plane wave by a homogeneous sphere. The transillumination of dentin does not exhibit a significant decrease in scattering from the ultraviolet to the infrared spectral range that can be attributed to enamel.[11] Therefore, imaging caries lesions at such high contrast is not possible in dentin.

A recently introduced diagnostic device, the DIAGNOcam (KaVo, Biberach, Germany, 2012), uses NIRT to visualize the different dental hard tissues and their condition in posterior teeth. Two near-infrared laser diodes with a wavelength of ~780 nm and a

A **B** **C**

Figure 1. Tooth 15 distal: A) no visual signs of a proximal caries lesion; B) bitewing radiograph: radiological translucence resembling a proximal caries lesion in the outer half of the dentin (D3); C) NIRT image: a squared shading in the enamel with linear contact to the dentino-enamel junction (Code 4)

power of 1 mW cm–2 transmit light through the alveolar bone and the dental hard tissue. An image of the transilluminated tooth is captured by a charge-coupled device sensor and displayed on a standard monitor (Figure 1). The image displays the tooth from the occlusal surface. High-contrast visualization of enamel caries is possible, whereas dentin caries lesions can only be visualized indirectly.[12]

In previous investigations, digital bitewing (DBW) radiography and NIRT presented equal clinical performance concerning the detection of proximal dentin caries in vivo.[12,13] Dentists require practical scoring or classification criteria for the reproducible documentation and monitoring of clinical findings. Therefore, a disease severity scale for proximal caries lesions assessed with NIRT was recommended for this purpose in 2014 (Table 1).[13] To date, only limited information regarding the diagnostic reliability of NIRT compared to DBW radiography has been available.[15] Therefore, the objective of this study was to analyse the inter- and intraexaminer reliability of proximal caries detection using DBW radiography and NIRT, including diagnostic decisions of multiple dentists. Moreover, different influencing variables, such as the involved methods, evaluation cycle, clinical experiences of the investigators and tooth type were included in our logistic regression analysis. The null hypothesis of this study was that no difference exists in the inter and intraexaminer reliability between DBW radiography and NIRT.

Digital bitewing radiography		Near-infrared transillumination	
Score	Description	Score	Description
0	No caries visible	0	No caries visible
D1	Caries in the outer half of enamel	1	First visible signs of caries within enamel
D2	Caries in the inner half of enamel	2	Sign of established caries with enamel
D3	Caries in the outer half of dentin	3	Caries with a point contact to the dentino-enamel junction
D4	Caries in the inner half of dentin	4	Caries with a linear contact the dentino-enamel junction
		5	Caries visible within dentin

Table 1. Caries diagnostic criteria for the assessment of digital bitewing radiographs[14] and near-infrared transillumination images[13].

Methods and materials

This in vitro reliability study used DBW and NIRT images from patients who were included in a previous clinical diagnostic study.[12] In this trial, 85 subjects (38 males and 47 females, mean age 25.0 years) with full permanent dentition and an overall healthy status were included. Each participant provided written informed consent. The local Ethics Committee approved this study (Project No. 013–12).

Image selection and reference diagnoses

In total, 211 image pairs consisting of DBW radiographs and their corresponding NIRT images were initially preselected according to the following criteria. All images were required to exhibit optimal contrast, brightness and sharpness. Each image exhibited at least one proximal surface with an adjacent tooth that was sound or showed varying degrees of proximal caries lesions. Furthermore, the relevant interproximal space of the selected images was depicted without significant overlapping effects. Surfaces with restorations, secondary caries, residual caries, hypomineralizations and orthodontic appliances were excluded. Before radiological assessment, each patient was asked whether DBW radiographs had been taken within the preceding 4 months. If these current images were available in sufficient quality, they were evaluated. In the case of present justifying indication, new DBW radiographs were made using an intraoral X-ray dental machine with a 203 mm tube (Heliodent DS, Sirona, Bensheim, Germany) including an X-ray field limitation (30 × 40 mm) with a charge-coupled device sensor (Intraoral II, sensor size 30.7 × 40.7 mm, Sirona, Bensheim, Germany). The exposure time was 0.06 s at a cathode voltage of 60 kV and an amperage of 7 mA. A sensor holding device (XPP-DS Digital Sensor Holders for Sirona, Dentsply Rinn, Elgin, IL) was used at all times.

Two investigators (JK and FL) provided a reference diagnosis for all of initially pre-selected pairs of DBW and NIRT images according to the given criteria in Table 1.[13, 14] Both analysed all images independently in two evaluation cycles under optimal conditions with calibrated monitors in a darkened room. Then, both investigators compared their results to determine a reference diagnosis for each surface. If the investigators reached different conclusions, they reassessed the images, discussed their points, and came to a consensus score. Finally, 100 image pairs with a well-balanced distribution of different lesion stages (34 sound, 33 enamel caries, and 33 dentin caries) were included to avoid any under- and overrepresentation of one caries stages.

All selected DBW and NIRT images were assigned to a unique identification number. Furthermore, a mark up was embedded on each image to highlight the relevant site, aiming to avoid misclassifications. To reduce the recognizability and memorability during the study period, each sequence of images was randomly changed between the first and second cycle of examinations for DBW and NILT images, respectively. The randomization list was only known to the principle investigators (JK and FL), who did not participate in the subsequent reliability study. All four image sequences were exported to separate PDF documents for the convenience of the participating dentists.

Reliability study

A group of 12 dentists with different professional status and clinical experience participated in this investigation. Four dentists had less than 2 years of clinical experience, four dentists had between 2 and 5 years of clinical experience, and four of had >10 years of clinical experience. Most of the investigators (N = 8) were employed at different universities, whereas the remaining four investigators worked in private practices. All received basic half-a-day theoretical and practical training sessions prior to participation. The dentists were introduced to the NIRT method. Furthermore, the study design and scoring criteria (Table 1)[13,14] were explained, and the dentists were trained. Subsequently, all 100 DBW radiographs and NIRT images were analysed in two evaluation cycles by all investigators with a minimum interval of 4 weeks to ensure blinding between the diagnostic decisions. Thus, a total of 2400 diagnoses were obtained for each method. All participants were encouraged to perform the evaluation without any help by other colleagues within 2 weeks. The image evaluation was performed on a standard calibrated monitor in a darkened room.

Statistical analysis

All scores from the dentists were entered in an Excel spreadsheet (Excel 2016, Microsoft, Redmond, WA). The data analysis was performed using SAS 9.3 (SAS Institute, Cary, NC) and R 3.3.2 (R Core Team, Vienna, Austria).[16] The descriptive analysis included the calculation and illustration of the percentage of agreement. Simple Kappa (κ) and weighted Kappa (wκ) coefficients were computed as measure of agreement to determine the inter- and intraexaminer agreement among the included investigators and in relation to the reference diagnoses (Tables 2 and 3).[17,18] Furthermore, to determine the reliability with reference diagnoses (Table 4), the values from all dentists ($N = 12$) were analysed in relation to the reference diagnoses and the κ coefficients were calculated. Fleiss–Cohen weights were used for the calculation of weighted κ coefficients.[18] κ-values were categorized as low (≤0.40), moderate (0.41 to 0.60), good (0.61 to 0.80), and excellent agreement (0.81 to 1.00).[19]

Furthermore, logistic regression analysis using a backward elimination model was performed for the outcome (correct/incorrect diagnosis in relation to consensus) vs measure. The analysis was adjusted for diagnostic method, evaluation cycle, experience and tooth.

Weighted κ for digital bitewing radiography		First evaluation cycle of each dentist												
		Reference diagnoses	1	2	3	4	5	6	7	8	9	10	11	12
Second Evaluation cycle of each dentist	Reference diagnoses	**1**	0.83	0.74	0.71	0.45	0.67	0.71	0.74	0.77	0.73	0.79	0.80	0.65
	1	0.79	**0.81**	0.77	0.68	0.44	0.62	0.67	0.72	0.72	0.73	0.72	0.72	0.69
	2	0.72	0.76	**0.72**	0.58	0.40	0.55	0.66	0.67	0.67	0.68	0.68	0.66	0.64
	3	0.77	0.80	0.74	**0.56**	0.49	0.66	0.78	0.80	0.75	0.78	0.73	0.72	0.70
	4	0.74	0.77	0.73	0.53	**0.49**	0.65	0.71	0.78	0.74	0.76	0.73	0.70	0.68
	5	0.71	0.76	0.73	0.51	0.49	**0.66**	0.73	0.78	0.80	0.78	0.77	0.73	0.66
	6	0.79	0.79	0.74	0.57	0.52	0.66	**0.79**	0.74	0.80	0.76	0.83	0.76	0.66
	7	0.68	0.71	0.75	0.52	0.45	0.63	0.74	**0.77**	0.73	0.76	0.73	0.67	0.58
	8	0.77	0.80	0.72	0.56	0.45	0.59	0.76	0.75	**0.83**	0.79	0.86	0.75	0.62
	9	0.79	0.77	0.75	0.63	0.44	0.64	0.75	0.71	0.73	**0.77**	0.73	0.72	0.71
	10	0.84	0.83	0.75	0.71	0.46	0.66	0.70	0.71	0.75	0.72	**0.85**	0.77	0.65
	11	0.84	0.82	0.74	0.63	0.51	0.66	0.71	0.75	0.81	0.77	0.80	**0.84**	0.66
	12	0.74	0.79	0.75	0.65	0.52	0.67	0.70	0.73	0.73	0.78	0.75	0.68	**0.81**

Bold numbers indicate intra-examiner values.

Table 2. Inter- and intraexaminer reliability values for digital bitewing radiography, which were calculated among all dentists and in relation to the reference diagnoses

Weighted κ for near-infrared trans-illumination		First evaluation cycle of each dentist												
		Reference diagnoses	1	2	3	4	5	6	7	8	9	10	11	12
Second Evaluation cycle of each dentist	Reference diagnoses	**1**	0.80	0.87	0.96	0.76	0.92	0.64	0.88	0.84	0.92	0.97	0.78	0.92
	1	0.85	**0.72**	0.80	0.88	0.69	0.84	0.56	0.83	0.83	0.89	0.83	0.76	0.85
	2	0.83	0.66	**0.78**	0.84	0.66	0.82	0.56	0.80	0.80	0.88	0.80	0.75	0.82
	3	0.83	0.69	0.77	**0.85**	0.66	0.83	0.60	0.85	0.81	0.83	0.84	0.75	0.87
	4	0.67	0.57	0.64	0.69	**0.58**	0.68	0.47	0.69	0.76	0.65	0.65	0.67	0.67
	5	0.84	0.69	0.81	0.87	0.67	**0.83**	0.54	0.82	0.82	0.89	0.82	0.75	0.84
	6	0.63	0.30	0.57	0.62	0.55	0.64	**0.72**	0.60	0.59	0.62	0.65	0.62	0.62
	7	0.85	0.66	0.79	0.86	0.66	0.85	0.54	**0.90**	0.85	0.85	0.83	0.78	0.86
	8	0.85	0.72	0.83	0.85	0.71	0.85	0.58	0.88	**0.96**	0.86	0.85	0.82	0.83
	9	0.87	0.67	0.80	0.87	0.71	0.85	0.56	0.80	0.81	**0.88**	0.85	0.75	0.87
	10	0.86	0.71	0.81	0.86	0.70	0.84	0.60	0.85	0.84	0.88	**0.85**	0.79	0.86
	11	0.76	0.59	0.77	0.78	0.67	0.77	0.60	0.78	0.79	0.75	0.76	**0.84**	0.78
	12	0.95	0.74	0.83	0.92	0.72	0.88	0.62	0.87	0.84	0.95	0.93	0.77	**0.90**

Bold numbers indicate intra-examiner values.

Table 3. Inter- and intraexaminer reliability values for near-infrared transillumination, which were calculated among all dentists and in relation

Variable	% agreement	Reliability with reference diagnoses			Intra-examiner reliability		
		Kappa	Weighted Kappa	p-value	Kappa	Weighted Kappa	p-value
DBW first evaluation	69.8%	0.60 (0.57–0.64)	0.74 (0.72–0.77)	<0.0001	0.64 (0.61–0.67)	0.77 (0.75–0.80)	0.0001
DBW second evaluation	72.4%	0.63 (0.60–0.67)	0.76 (0.74–0.79)	<0.0001			
NIRT first evaluation	79.0%	0.74 (0.71–0.77)	0.86 (0.84–0.88)	<0.0001	0.68 (0.65–0.71)	0.84 (0.82–0.85)	0.004
NIRT second evaluation	71.2%	0.64 (0.61–0.67)	0.82 (0.80–0.84)	<0.0001			

DBW, digital bitewing; NIRT, near-infrared light transillumination. The percentages of agreement and κ-values were calculated for all investigators in relation to the reference diagnoses.

Table 4. Overall inter- and intraexaminer reliability values for digital bitewing radiography and near-infrared transillumination

Results

An overview of all diagnostic decisions in relation to the reference diagnoses is presented in Figure 2. Most diagnostic decisions of DBW radiography and NIRT were registered on the diagonals. Incorrectly classified diagnoses exhibited a deviation in most cases of only plus/minus one diagnostic score and were found in one of the neighbouring diagnostic categories. An insignificant number of incorrect diagnoses differed by up to three categories.

Tables 2 and 3 present the intra- and interexaminer reliability based on wκ values for DBW radiography and NIRT (the κ-values exhibited a similar distribution; data not shown). Analyses of all interexaminer data of the first evaluation cycle revealed that 69.8% of the DBW radiographs and 79.0% of the NIRT images were correctly assessed. The second evaluation cycle presented a concordant diagnosis of 72.4% for the DBW radiographs and 71.2% for the NIRT images. The level of agreement of the diagnoses in the second evaluation cycle increased for DBW radiographs but was reduced for NIRT images (Table 4). The interexaminer wκ increased from 0.74 to 0.76 for the evaluation of DBW radiographs and decreased from 0.86 to 0.82 for NIRT images.

According to the binomial logistic regression, the diagnostic method and the evaluation cycle significantly influenced the reliability. NIRT images [adjusted odds

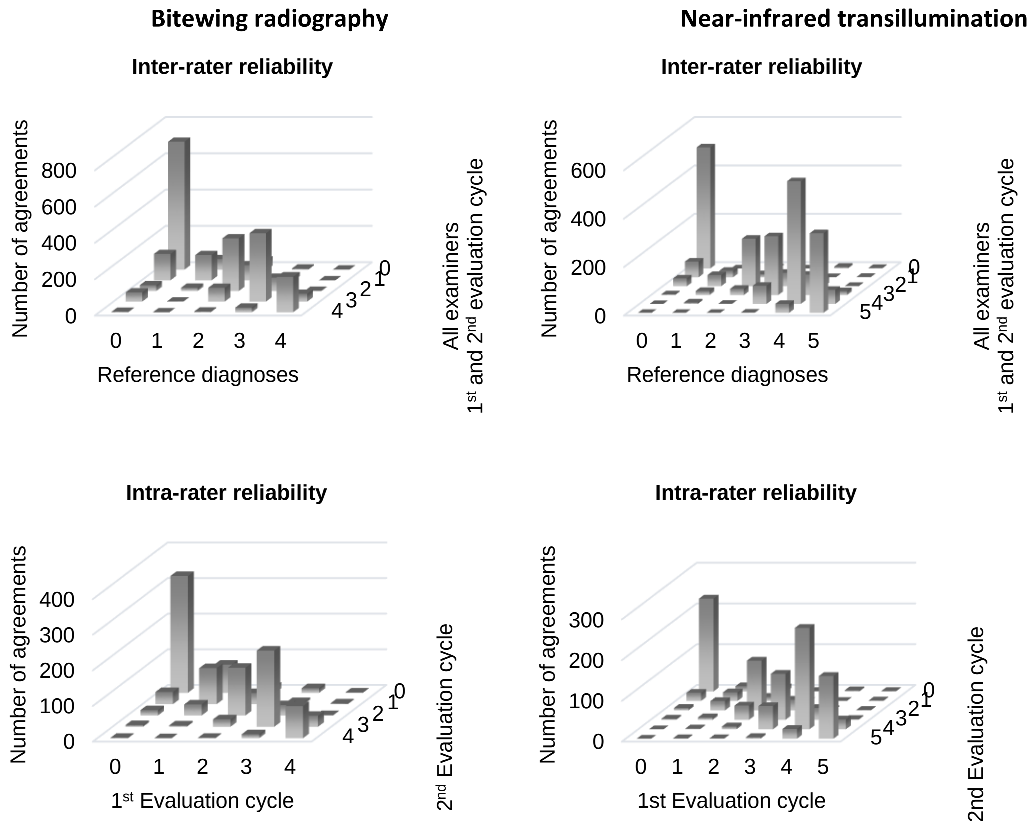

Figure 2. Illustration of inter- and intraexaminer agreement for digital bitewing radiographs and near-infrared transillumination images between the first and second evaluation cycles and the relationship to the reference diagnoses.

ratio (aOR) 0.82] had a higher likelihood of being correctly diagnosed, whereas NIRT diagnoses of the second evaluation cycle (aOR 1.12) were more likely incorrect. Clinical experience or the tooth type did not have any significant effect on the accuracy of the diagnosis.

Discussion

In this study, we aimed to investigate the inter- and intraexaminer reliability of DBW radiography and NIRT for caries detection and assessment on proximal surfaces. We hypothesized that both methods exhibited similar results for inter- and intraexaminer reliability. In general, both diagnostic methods revealed good to excellent reliability (Figure 2 and Tables 2–4). When comparing the reliability of both methods, good wκ values were obtained for inter- and intraexaminer reliability of DBW radiographs.

Co-variables	Groups	aOR	95% CI	p-value
Diagnostic method	DBW	1	-	-
	NIRT	**0.82**	**0.72-0.93**	**0.002**
Evaluation cycle	First examination	1	-	-
	Second examination	**1.14**	**1.00-1.30**	**0.04**
Clinical experience	0-1 year	1	-	-
	2-5 years	0.96	0.80-1.32	0.85
	>5 years	0.93	0.74-1.18	0.55
Tooth type	Molars	1	-	-
	Premolars	0.94	0.79-1.13	0.51

aOR, adjusted odds ratio; CI, confidence interval; DBW, digital bitewing; NIRT, near-infrared light transillumination. Bold numbers illustrate a significant influence.

Table 5. Adjusted odds ratio with corresponding 95% CI; p-values were computed according to the logistic regression model using backward elimination

Good and even excellent wκ values were more frequently obtained for NIRT images. The analysis of inter- and intraexaminer reliability of DBW radiography and NIRT revealed results in or better than the typical range of previously published studies.[15, 20–22]

Considering the results from all κ statistics and the logistic regression analysis, the initially formulated hypothesis must be rejected. NIRT exhibited significantly better inter- and intraexaminer reliability than DBW radiography (Tables 4 and 5). A possible interpretation for this finding might be that enamel caries lesions on proximal sites imaged with NIRT exhibited unambiguous characteristics. Therefore, it might be argued that little room for interpretation existed, as often occurs on DBW radiographs with early lesions. Previous studies have demonstrated that DBW radiographs have less contrast, resulting in relatively low sensitivity values.[23] This observation is consistent with recent experiences from dental practice. For example, enamel caries lesions are easily detected on NIRT images, but the corresponding DBW image does not exhibit any clear indications of the presence of proximal demineralizations. This notion might be a possible explanation for the slightly weaker reliability of DBW radiography in this study.

Furthermore, we analysed the influence of certain co-variables on reliability. Apart from the above-mentioned, significance of the diagnostic methods, the logistic regression model revealed that only the cycle of examination had a significant influence on reliability (Table 5). The first cycle of examination (aOR 1.0) was associated with an increased likelihood of a correct diagnosis compared to the second examination (aOR 1.14). This result was predominately supported by the data of the NIRT method (Table 4). In contrast to this finding, κ and wκ values were slightly but significantly higher in the case of DBW radiography. When explaining these findings, it should be noted that one could expect a moderate increase in the reliability between the first and second evaluation cycles in such a study. This effect could be attributed to learning and memory effects, given that the examiners can remember previously observed images. Furthermore, a training course and participation in a study could increase the awareness of each investigator, which may result in better clinical diagnostics. When considering such effects, the results from DBW radiography are consistent with this assumption. In contrast to this finding, the significantly lower reliability values of NIRT images are difficult to explain. An unproven hypothesis could be that all examiners made greater efforts to assess the NIRT images correctly during the first investigation and neglected the importance of the second course. However, this assumption contrasts with the findings of the DBW radiography images.

Our research exclusively investigated the reliability of DBW radiography and the new NIRT method for proximal caries detection and assessment with inclusion of different co-variables (Table 5). Another strength of our study design is the inclusion of 12 examiners and 100 image pairs. Each evaluation cycle was randomly sorted to eliminate recognizability and memorability effects. Each evaluation cycle was blinded and randomized with a 4-week time interval before the next cycle to avoid any active influence by the examiners. Another unique feature of this study was the use of a logistic regression model to weight the influence of any co-variables. We had performed the power calculation for the DBW data alone using the R package kappaSize, because the sample size calculation for reliability studies is clear when the number of raters are two or more, with an equal number of ratings per subject and a maximum of five categories (DBW with five vs NIRT with six categories).[24,25] Having

100 specimens in this study would have a power over 80% even after considering the presence of six categories with the NIRT technique. In addition, one critical argument is that the principal investigators chose all DBW and NIRT images subjectively based on strict quality criteria. We aimed to select unambiguous cases that were not negatively influenced by fuzziness, overlapping or any additional diagnoses. Therefore, this selection strategy might not be representative of clinical practice, where often less-than-perfect images need to be assessed. It could also be argued that the image selection had a positive influence on the documented reliability data. No validation of caries extension was performed as this would require an invasive evaluation of healthy surfaces in vivo or those with non-cavitated caries lesions which can not be justified due to ethical reasons.

Conclusions

In addition to its strengths and limitations, this study revealed a good to excellent inter- and intraexaminer reliability for proximal caries detection using DBW and NIRT images. The logistic regression analysis revealed significantly better reliability for NIRT. In addition, the first evaluation cycle was more reliable than the second according to the reference diagnoses.

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Eidesstattliche Versicherung

Lederer, Alexander

Ich erkläre hiermit an Eides statt, dass ich die vorliegende Dissertation mit dem Thema

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München, 25.07.2019 Alexander Lederer