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Near-infrared hyperspectral imaging of water evaporation dynamics for early detection of incipient caries

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ABSTRACT

Objectives: Incipient caries is characterized as demineralization of the tooth enamel reflecting in increased porosity of enamel structure. As a result, the demineralized enamel may contain increased amount of water, and exhibit different water evaporation dynamics than the sound enamel. The objective of this paper is to assess the applicability of water evaporation dynamics of sound and demineralized enamel for detection and quantification of incipient caries using near-infrared hyperspectral imaging.

Methods: The time lapse of water evaporation from enamel samples with artificial and natural caries lesions of different stages was imaged by a near-infrared hyperspectral imaging system. Partial least squares regression was used to predict the water content from the acquired spectra. The water evaporation dynamics was characterized by a first order logarithmic drying model. The calculated time constants of the logarithmic drying model were used as the discriminative feature.

Results: The conducted measurements showed that demineralized enamel contains more water and exhibits significantly faster water evaporation than the sound enamel. By appropriate modelling of the water evaporation process from the enamel surface, the contrast between the sound and demineralized enamel observed in the individual near infrared spectral images can be substantially enhanced.

Conclusions: The presented results indicate that near-infrared based prediction of water content combined with an appropriate drying model presents a strong foundation for development of novel diagnostic tools for incipient caries detection.

Clinical Significance: The results of the study enhance the understanding of the water evaporation process from the sound and demineralized enamel and have significant implications for the detection of incipient caries by near-infrared hyperspectral imaging.

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1. Introduction

Dental caries is a chronic disease, initially characterized as demineralization of enamel, which is still very difficult to diagnose, especially at the earliest stages when the disease could be completely cured leaving no damage to the dental structure.[1] Most frequently used diagnostic methods for caries detection are primarily based on subjective interpretation by visual inspection and tactile examination, aided by radiographs. These methods are able to detect only relatively advanced caries lesions, involving as much as one-third or more of the enamel thickness.[2]

Currently, there is a great demand for more reliable diagnostic tools for early detection of enamel demineralization. Among these, near-infrared (NIR) spectroscopy stands out for the ability to characterize and differentiate between different hard dental tissues and stages of caries lesions based on the distinct spectral features of the sound and diseased hard dental tissues.[3–7] Moreover, dental enamel manifests low absorption and scattering of NIR light, therefore, NIR spectroscopy is also well suited for non-invasive early detection of interproximal caries, or under-surface caries, located even up to 1.5 mm below the enamel surface.[8–10] State-of-the-art spectrographs and tunable filters provide the means to extend NIR spectroscopy to hyperspectral imaging, which provides more accurate spatial and spectral information on the structure of sound and diseased dental tissues. However, the intra- and inter-patient spectral variability of the sound and especially diseased dental tissues can be substantial. The large variability may be due (but not limited) to different structure, mineralization, surface properties, enamel thickness, pathological changes and in particular the water content of the hard dental tissues.

Water in the dental tissues may exist in two states, as loosely bound or as tightly bound water.[11–14] The two types of water are also frequently referred to as adsorbed water and structural water, respectively.[15] The adsorbed water content can reversibly vary for temperatures under 200 °C without producing changes in the dental structure. On the other hand, the structural water content is irreversibly reduced in the temperature range from 200 °C to 400 °C resulting in changes to the dental structure.[14] In oral environment, the enamel contains 3 wt% water, while the dentine contains 5 wt% water.[16]

In the NIR spectral range, water has a significant absorption band at about 1460 nm, therefore, any change in the water content of the enamel or dentine directly reflects in the corresponding NIR spectra. Near infrared hyperspectral imaging systems commonly use broadband halogen light sources which can accelerate the process of adsorbed water evaporation and thereby lead to significant changes in the water content of the hard dental tissue during the acquisition of consecutive hyper-spectral images. Loss of water in enamel also reduces its transparency at all NIR wavelengths and thereby significantly affects the contrast between the sound and demineralized enamel.[17] Therefore, development of NIR spectroscopy-based automated classification methods suitable for deployment in a clinical setting requires assessment of the dental tissues water content.[18] By appropriate modelling, the influence of water content on the performance of the dental tissue classification can be minimized.

Previous studies have investigated thermal imaging in the spectral range from 3.6 μm to 13 μm for quantification of smooth surface and occlusal caries lesion severity based on the time lapse of the thermal response induced by forced water evaporation from the tooth surface.[19,20] The rate of water loss from the demineralized enamel was found to be related to the caries lesion activity, as the arrested caries lesions are less permeable to water due to the highly mineralized outer layer covering the caries lesion. The enamel lesion activity was also assessed by quantitative laser fluorescence (QLF), which differentiates between the active and arrested caries lesions based on the enamel auto fluorescence signal intensity, observed during the first few seconds of the forced water evaporation from the enamel surface.[21,22]

However, the existing methods employing QLF and thermal imaging are limited to detection of water content changes near the enamel surface and have difficulties to recognize under-surface caries lesions. In contrast, imaging in the NIR spectral range, has been shown to provide useful information from the surface and deeper layers of enamel, and is highly sensitive to the water content of the hard dental tissues. Therefore, we hypothesize that early caries lesions could be detected by NIR hyperspectral imaging of the water evaporation process from the enamel. For this purpose, we used the acquired time-resolved spectral information and the corresponding sample mass measurements to model the enamel water content and study the water evaporation process from the sound and demineralized enamel.

2. Materials and methods

2.1. *Sample preparation*

All the 24 teeth used in this study were from different subjects. The teeth were thoroughly cleaned and stored in distilled water containing thymol. Prior to acquisition of hyperspectral images the samples were gently wiped off using a cotton roll. The average ambient temperature and humidity during the acquisition of hyperspectral images were 23 °C and 65%, respectively. The 24 teeth were split into three sets.

The first set comprised 20 extracted human teeth free of caries, cracks, and enamel malformations which were cut into 1.0 mm thick axial slices. The slices were used to train the water content prediction model estimating the water content of enamel from the acquired NIR spectra.

The second set comprised three extracted human teeth, free of caries, cracks, and enamel malformations, which were longitudinally cut into halves and used to produce artificial caries lesions. One half of each tooth was exposed to 6 days of artificial demineralization following an established demineralization procedure,[23,24] while the other half served as the control sample and was kept in distilled water with thymol. A constant-temperature incubator without agitation was used to maintain the temperature of the samples and demineralizing solution at 25 °C. The demineralizing solution was prepared from 100 mmol/L lactic acid, 18.0 mmol/L calcium