The detection threshold of non-contacting laser profilometry and characterisation of microscale surface changes in natural human enamel following citric acid-mediated attack

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Abstract. In this study we quantify the detection threshold of non-contacting laser profilometry (NCLP) in measuring changes to surface form and roughness of natural (unpolished) human enamel samples. We additionally determine and quantify the effects of thermal variation on NCLP laser sensor displacement according to short, medium, and long-term scanning intervals and thus outline its implications for dental erosion studies utilising short-duration acid-attack models. We describe a new model for the utilisation of natural human enamel samples and characterise the effects of short and medium-term acid-attack on surface form and roughness of natural enamel using NCLP, optical coherence tomography (OCT), and tandem scanning confocal microscopy (TSM).

Introduction

NCLP is considered the gold standard measurement technique for the detection and quantification of surface wear in dental tribology and dental erosion studies of acid-mediated attack on dental hard tissue samples [1–3]. Previously, dental erosion studies have focused on quantifying the effects of long-duration acid-mediated erosion on polished enamel samples as the scale of subsequent wear is relatively large and uniform, and thus well within the detection threshold of current NCLPs. However, the anticipated effects of early-duration acid erosion, considered of more clinical relevance, may occur at the micron or sub-micron level and may potentially be at the limit of current NCLP detection threshold. In dental erosion studies, the resolution (detection threshold) of NCLPs is primarily determined by the laser spot size (of the laser displacement probe) [4] which determines spatial (XY) resolution, and the lateral precision [4] of the motion system used which in-turn determines the repeatability of measurements. Thermal variation during the period of the measurement is considered one of the largest sources of measurement error in surface metrology and can have significant impact on the NCLP measurement capability in early-duration acid erosion studies where, the detection of submicron scale changes in surface texture or form is paramount [4]. Additionally, whilst the polished enamel surface has been the substrate of choice for almost all previous dental erosion studies due to its ease of preparation, barrier creation, and subsequent characterisation using NCLP, the utilisation of natural (unpolished) enamel could provide a more clinically relevant substrate to determine the effect of acid-mediated attack on human enamel.

Therefore, this study sought to determine the detection threshold of non-contacting laser profilometry (NCLP) in measuring changes to surface form and surface roughness in natural human enamel in vitro, determine the effect of thermal variation on NCLP measurement, and characterise the surface changes following acid-mediated erosion.

Materials and Methods

Repeatability and reproducibility accuracy of NCLP was determined by consecutive scanning of natural human enamel samples with/without sample repositioning. The ambient thermal variation and NCLP sensor displacement change over short (30 seconds), medium (20 minutes), and long (2 hours) scanning periods were evaluated for their standard deviation. Natural human enamel specimens (n=12) were eroded using citric acid (0.3% pH3.2) for 5, 10, and 15 minutes. Resulting lesions were characterised using surface profilometry to determine surface profile (3D step height) and roughness (S_a) changes, optical coherence tomography (OCT) to determine changes in surface reflectivity, and tandem scanning confocal microscopy (TSM) for macroscopic morphology determination.

Results

Repeatability and reproducibility error of NCLP for surface form was 0.279 µm and 0.431 µm, whilst for surface roughness this was 0.072 µm and 0.084 µm. Thermal variation in scanning conditions (see Fig 1) resulted in NCLP sensor displacement of 0.556 µm and 1.049 µm over medium and long scanning periods respectively. Wear scar depth were calculated between 0.72 – 1.61 µm at 5 minutes, 1.72 – 3.06 µm at 10 minutes, and 3.40 – 7.06 µm at 15 minutes (see Fig 2). Qualitative image analysis indicated erosive change at the surface level, with surface reflectivity decreasing and macroscopic surface morphology alteration, progressing after increasing erosion time.

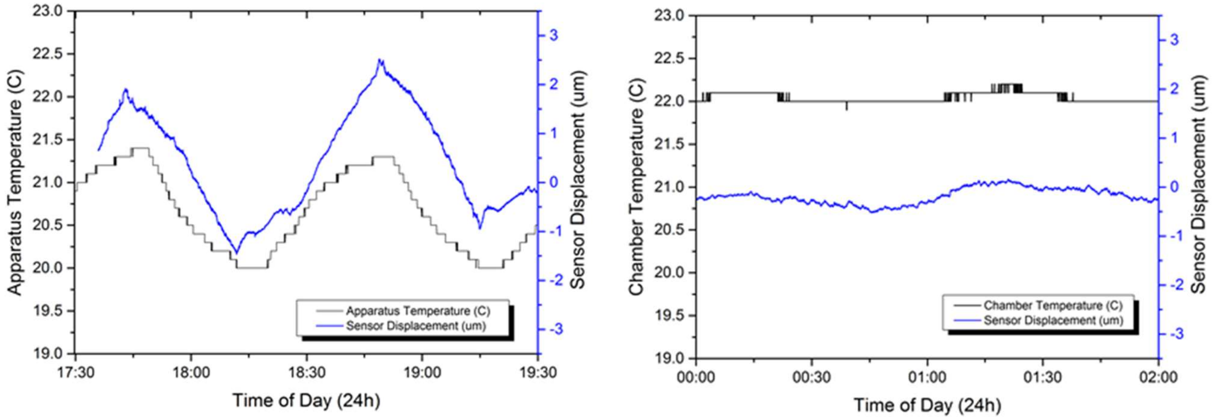

Figure 1 - *Graphs of apparatus ambient temperature and the sensor displacement without apparatus enclosure (a) and with apparatus enclosure (b), indicating a relationship between sensor displacement and apparatus ambient temperature. The use of a thermal enclosure leads to a significant reduction in chamber and apparatus temperature variation which in turn minimises sensor displacement, resulting in a more stable scanning outcome.*

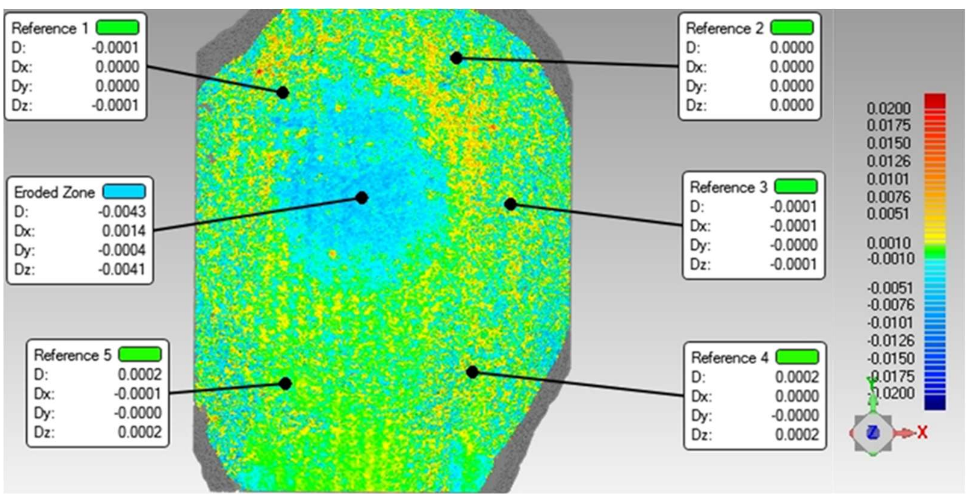

Figure 2 - *Representative example of a sample with its associated wear scar in blue, green denotes no change, whilst yellow denotes gain post erosion. Wear scar depth is depicted by 3D total deviation (D) and Z-deviation (Dz). The central eroded region and 5 reference regions have been analysed for allow for erosion versus non-eroded comparison. This indicates a wear scar depth of 4.3 µm.*

Conclusion

This study demonstrated the minimum detectable limits for NCLP in measuring surface form and roughness changes. Additionally, the effects of ambient thermal variation and subsequent senor displacement and their effects on surface profile measurements were characterised for the first time. The quantification of bulk enamel loss (step height) in natural human enamel after citric acid erosion was determined within NCLP and temperature operating limits.

Acknowledgement

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