DENTAL MATERIALS XXX (2018) XXX–XXX

Available online at www.sciencedirect.com

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Intracoronal stress transfer through enamel following RBC photopolymerisation: A synchrotron X-ray study

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ARTICLE INFO

Article history:
Received 1 May 2018
Received in revised form
29 July 2018
Accepted 29 July 2018
Available online xxx

Keywords:
Synchrotron X-ray micro-focussed diffraction
Resin based composite
Photo-polymerisation
Enamel
Stress
Strain
Shrinkage

ABSTRACT

Objectives. To measure the spatial distribution of crystallographic strain in tooth enamel induced by the photo-polymerisation of a dimethacrylate resin based composite cavity restoration.

Methods. Six sound first premolar teeth, allocated into two groups (n = 3), were prepared with mesio-occlusal distal cavities. The enamel was machined at the point of maximum convexity on the outer tooth to create a vertical fin of thickness 100 μm and 0.5 mm depth to allow for synchrotron X-ray diffraction measurements. 2D diffraction patterns were used to determine crystallite orientation and quantify changes in the hydroxyapatite crystal lattice parameters, before and after photo-polymerisation of a composite material placed in the cavity, to calculate strain in the respective axis. The composite was photo-polymerised with either relatively high (1200 mW cm^{-2}, group 1) or low (480 mW cm^{-2}, group 2) irradiances using LED or quartz halogen light sources, respectively. A paired t-test was used to determine significant differences in strain between irradiance protocols at $\alpha = 0.001$.

Results. Photo-polymerisation of the composite in the adjacent cavity induced significant changes in both the crystallographic *c* and *a* axes of the enamel measurement area. However the magnitude of strain was low with ~0.1% difference before and after composite photo-polymerisation. Strain in enamel was not uniformly distributed and varied spatially as a function of crystallite orientation. Increased alignment of crystallites perpendicular to the cavity wall was associated with higher *c* axis strain. Additionally, strain was significantly greater in the *c* ($p < 0.001$) and *a* axis ($p < 0.001$) when using a high irradiance photo-polymerisation protocol.

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https://doi.org/10.1016/j.dental.2018.07.005

Significance. Although cuspal deflection is routinely measured to indirectly assess the 'global' effect of composite shrinkage on the tooth-restoration complex, here we show that absolute strains generated in enamel are low, indicating strain relief mechanisms may be operative. The use of low irradiance protocols for photo-polymerisation resulted in reduced strain.

1. Introduction

Dental resin based composite materials exhibit a volumetric shrinkage associated with polymerisation that, when constrained by adhesion to the tooth cavity walls, leads to the generation of shrinkage stresses within the tooth-composite complex. Shrinkage stresses have been measured directly in-vitro and it has been identified that the magnitude and kinetics of their development are dependent on a number of factors, including in particular, the composite composition and resin chemistry [1,2], photo-polymerisation variables [3–5] and the terminal degree of monomer to polymer conversion [6–8]. It has been proposed that both the magnitude of the shrinkage stress, and the kinetics of its development, are important factors in determining whether shrinkage stresses have an unfavourable impact on the remaining tooth tissue or on the adhesive interface between the composite and enamel and dentine. Stress transfer to the adhered tooth complex has been directly demonstrated using cuspal deflection methods and indirectly indicated through micro-leakage measurements [9–14] which are proposed to reflect interfacial debonding that has occurred as a stress relief mechanism [15–18]. Shrinkage stresses arise because the volumetric free shrinkage of the polymer matrix of composites that occurs during polymerisation is constrained by the geometrical confines of the host tissue substrate to which it is adhered [19–21]. It is accepted that the magnitude of stress generated is influenced by the monomer composition [1,5,22,23], the polymerisation rate [24–28], the stiffness of the polymerised cross-linked matrix and the nature of the external constraints [29–34], which can also be considered as the compliance of the system [35,36]. Of these factors, the effects of resin–matrix monomer composition, polymerisation kinetics and subsequent mechanical properties of the composite including its adhesion to the tooth substrate have arguably been disproportionately studied, when compared with understanding stress transfer to the tooth and potential stress relief mechanisms within the tooth-restoration complex.

The tooth is a structure comprised of a highly mineralised (94–96 wt% hydroxyapatite [37,38]) thin surface layer of enamel which is supported by a relatively compliant, less mineralised (~70 wt%) dentine substrate [39]. At the interface, adhesion between enamel and dentine is manifested by a hierarchically scalloped topology and a relatively protein rich organic matrix [40–43]. Enamel and dentine and their interface are subjected to extreme cyclic mechanical and thermal stresses. However, they show remarkable resistance to mechanical failure [44,45]. Notably enamel has no cellular mediated capacity for repair but it is proposed that its hierarchical structure provides an inherent ability for stress relief conferring a damage tolerance that enables it to survive for the lifespan of the host [46,47]. Enamel structure is comprised of nanoscale hydroxyapatite needle-like crystallites that are specifically orientated to form microscale 'keyhole shaped' prisms [38,39,48,49], that are separated from each other by less organised, protein rich interfaces [50–52]. Both hydroxyapatite crystallites and enamel prisms have distinct orientations that are a function of their location [53–55]. As a bulk material, enamel is anisotropic with respect to its elastic modulus [56], exhibits a high fracture toughness [57] and has been shown to exhibit time dependent deformation as a response to applied stress. Using nano-indentation methods it has been shown that the creep behaviour of enamel was more similar to metallic materials than to its hydroxyapatite constituent [38]. These responses were attributed to the organic protein content, found between hydroxyapatite crystals and between prisms, which permitted both inelastic deformation and subsequent partial recovery of the deformation [58,59].

The capacity for stress relief within the enamel structure may go some way to explaining the inconsistencies in data generated from the cuspal deflection method [27,28,60–63] using natural teeth. Cuspal deflection measurements typically require a large mesio-occlusal-distal (MOD) cavity to be prepared in a tooth and the distance between the points of maximum convexity of the facial and lingual surfaces to be recorded dynamically during composite placement and photo-polymerisation [32–34,36,64]. The magnitude of the decrease in inter-cuspal distance is used as a surrogate outcome of the net shrinkage stress generated and distributed within the tooth-composite complex. Such measurements cannot discriminate the vector and location of stress generation and indeed any stress relief that occurs, within the tooth, the composite or the interface between materials. A number of cuspal deflection studies have failed to show differences between variables that were strongly assumed to generate different magnitudes of shrinkage stress [62,63].

The aim of this study was for the first time to measure strains within the enamel that had been induced by the polymerisation of dental composites. Using two-dimensional synchrotron X-ray diffraction (2D-SXRD) it is possible to measure simultaneously lattice strain and crystallite organisation by observing the changes in lattice parameters and preferred orientation of the crystalline phase (hydroxyapatite). The specific objective was to quantify the spatial distribution of strain generated in the hydroxyapatite lattice of human dental enamel. Photo-polymerisation of a single composite material was induced using two different irradiances, nominally considered as 'high' and 'low' to generate differences in the kinetics of shrinkage stress generation [7,65].

Please cite this article in press as: Al-Jawad M, et al. Intracoronal stress transfer through enamel following RBC photopolymerisation: A synchrotron X-ray study. Dent Mater (2018), https://doi.org/10.1016/j.dental.2018.07.005