Metallic proxies remain unsuitable for assessing the mechanics of microwear formation: reply to comment on van Casteren et al. (2018)

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1. Introduction

A debate has recently developed concerning mechanisms of dental microwear formation. Lucas et al. [1] predicted and demonstrated that phytoliths (microscopic plant silicates) are too soft to wear tooth enamel on initial contact. Rather they should plastically deform (i.e. rub) enamel such that any wear would be the result of fatigue caused by multiple loadings. Xia et al. [2] repeatedly slid macroscopic aluminium and brass balls across enamel and observed seemingly abrasive striations. Because the balls are rounded and both metals measured as softer than enamel, Xia et al. [2] claimed to have falsified the model of Lucas et al. [1]. van Casteren et al. [3] countered that the surfaces of the aluminium balls were coated by a hard, brittle, irregular oxide that would fragment easily and abrade enamel. We also
found that the brass balls were likely to have been work hardened and may have rubbed rather than directly abraded enamel, and that the high number of sliding trials conducted by Xia et al. [2] might have produced abrasion by fatigue. Subsequently, Xia et al. [4] criticized the methods and hardness measurements of van Casteren et al. [3] and presented results from single slide experiments claiming abrasion. We respond below.

First, it is incontrovertible that the aluminium balls in question are coated by an oxide layer, as shown by energy-dispersive X-ray spectroscopy [2,3], and it is known that aluminium oxide is much harder than aluminium [5]. Furthermore, it is unsurprising that machining processes for producing ball bearings could result in work hardening. These facts alone support our contention that ‘metallic proxies are unsuitable for assessing the mechanics of microwear formation’ [3, p. 1]. If one wanted to test our assertion that phytoliths cannot directly abrade enamel [1], then the obvious course of action is to slide phytoliths against enamel. In the absence of such experiments, the debate is reduced to materials science and contact mechanics minutiae rather than biologically significant mechanics.

Xia et al. [4] cite Hernot et al. [6] to argue we used the wrong formula in our hardness calculations. However, the magnitude of error is negligible as our plots are of the contact pressure during initial elastic loading (at only a few nm of depth) and the onset of the first pop-in event, not when sinking-in or pile-up is occurring about the indenter (the condition addressed by Hernot et al. [6]). Indeed, Xia et al. [4, p. 3] note that, ‘...the formula [used by van Casteren et al. [3]] is accurate only when the indentation process is fully elastic.’ Our experimental conditions satisfy this criterion. Moreover, the appropriate measure of a Berkovitch indenter tip when estimating the depth of ‘spherical’ contact is the effective conical angle, which is 70.3°. Thus, their comment about the depth at which we can accurately infer pressure is invalid.

Ironically, Xia et al. [4] measure hardness by relying only on the unloading curve as their basis for interpretation of the contact stresses, yet loading curves for aluminium [2,3] show instances of pop-in behaviour and changes of slope indicative of a hard surface layer. Thus, Xia et al. [4] have penetrated the layer they purport to be measuring and have recorded the hardness of the softer, underlying metal.

Xia et al. [4] are concerned that the tip radius of our indenter [3] was too large, and they advise calibrating the size of an indenter tip against an area function. Their indenter tip was ostensibly sharper than that used by van Casteren et al. [3], but in fact, their own loading curve data and (now corrected) area function indicate their tip is extraordinarily blunt (figure 1). The area curve from van Casteren et al. [3] shows that the tip used by us is somewhat blunter than manufacturer’s specifications, and we have updated our pressure/hardness data accordingly. Even using the updated calculation (figure 2), pressure on the oxide layer is in the range of enamel after a depth of only approximately 4 nm in the trial whose loading curve shows no sign of pop-in cracks, and the hardness of enamel is certainly exceeded by approximately 9 nm. This is reasonably only a minimum estimate of the oxide hardness, because the pressure is a function of the thin layer flexing on the surface of the softer, underlying metal. Pop-in cracks indicate that the oxide is fracturing soon after, so pressures at greater depth are irrelevant to the hardness of the oxide. van Casteren et al. [3] discussed the difficulty inherent in
measuring the hardness of such thin surfaces, which in and of itself is indicative of the inappropriateness of using metal balls as a proxy for phytoliths. Xia et al. [4] took no steps to address this issue. Xia et al. [4] pointed to enamel chips as evidence of abrasive wear caused by their brass single sliding experiments. They do not report the size of these chips, but they can hardly be visualized in their figure 5e. Based on their now corrected scale, we surmise that these chips are perhaps several tens of nm in diameter. By contrast, Lucas et al. [1] found that sliding quartz dust across enamel produced multiple enamel chips of approximately 2 μm in diameter, but that no such chips were observed when sliding phytoliths across equivalent surfaces. The volume of enamel contained in a 2 μm diameter chip is orders of magnitude greater than that contained in a chip whose diameter is approximately 50–100 nm. Thus, although Xia et al. [4] have shown that a brass ball can produce nano-scale damage, they have not demonstrated micro-scale wear. It is the micro-scale that is relevant both to the mechanical model of Lucas et al. [1] and to dental microwear analysis generally. van Casteren et al. [3] discussed the issue of scale but Xia et al. [5] have seemingly ignored the point.

In summary, sliding experiments using metallic balls present little useful data for testing the hypothesis of Lucas et al. [1]. An understanding of how biological materials affect teeth should be based on analyses of biological materials.

Data accessibility. The datasets supporting this article have been uploaded as part of the electronic supplementary material.

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