Design Rules for a Self-Healing Bone Cement

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Statement of Purpose: Biological materials such as skin, bone, and muscle are capable of *in situ* self-healing through cycles of consumption and regeneration that prevent the accumulation of defects that arise as the tissue ages and becomes fatigued[1]. Biomaterials are subjected to the loading and degradation effects of the body; the development of synthetic biomaterials with the intrinsic ability to self-repair mechanical and chemical damage would be particularly useful in implants that replace tissues capable of self-repair in their native, healthy states. Such materials would possess the potential for significantly extending implant lifetimes by avoiding catastrophic failures initiated by accumulated microcracks; they should be designed to sense, halt, and even reverse damage, ideally without requiring the application of external stimuli. A repolymerization approach to self-healing is summarized in Figure 1 and adapted from (2). (a) A polymer matrix embedded with catalyst and encapsulated healing agent is compromised by (b) an infiltrating microcrack that exposes embedded catalyst and (c) continues to propagate, fracturing a microcapsule, releasing the healing agent into the crack plane, resulting in (d) the polymerization of the healing agent that halts crack propagation. Orthopedic, dental, and cardiovascular implants that undergo cyclic loading and subsequent failures could be significantly improved through the application of this approach to the design of biomaterials.

Methods: Cemented joint replacements are subject to failures stemming from the production of wear particles from the articulating surface and bone cement; these particles can be caught in the joint space, increasing abrasion and accelerating the rate of wear[3]. Poly(methyl methacrylate), PMMA, is commonly used as a bone cement in total joint replacement surgeries; it has good biocompatibility and integrates well with bone but is subject to microcracking following sustained cyclic loading commonly seen with such implants[3]. The addition of an encapsulated healing agent would toughen the matrix and provide the means to repair microcracks, thereby halting the production of wear particles and ultimate failure of the implant. Cyanoacrylate used as tissue adhesives is a potential candidate healing agent because it rapidly polymerizes with water, forming a watertight seal without requiring an additional catalyst. It can be dissolved with organic solvents such as acetone, nitromethane, ethanol, chloroform, and γ-butyrolactone[4]; various oil-in-solvent emulsion approaches exist to encapsulate a substance of interest and could be used for this application.

Results: Scanning electron microscopy and optical microscopy have been used to determine the size distribution and shell thickness of microcapsules, as well as the volume of encapsulated agent. Investigators have reported the creation of self-healing systems using an epoxy matrix embedded with Grubbs' catalyst and encapsulated dicyclopentadiene (DCPD)[2]. Release of the DCPD healing agent from urea-formaldehyde (UF) capsules was visualized and the regeneration capabilities of the matrix were assessed using tapered double-cantilever beam experiments; an average of 73% of the virgin fracture toughness was recovered following healing[2]. These results support the theory that this approach can achieve healing, thereby validating its potential usage in biomaterials.

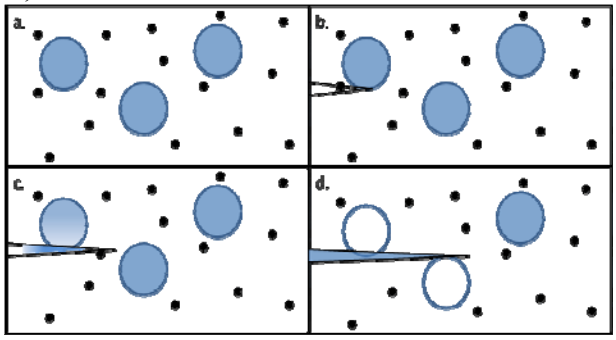

Figure 1. Self-healing via repolymerization

Conclusions: Previous research has verified that this repolymerization approach yields the return of material strength and function[2]. However, these designs do not employ materials that adhere to the constraints presented by biomaterials. The first step towards our creation of a self-healing PMMA bone cement is the successful encapsulation of cyanoacrylate; this will require optimization studies to find the ideal solvent and capsule material. Our future studies will assess the properties of the capsules with regards to shell thickness, size distribution, and the volume of cyanoacrylate contained within them. Stability of the cyanoacrylate within the capsules and the ability of the spheres to rupture under the forces generated through crack propagation are also issues to be considered. Furthermore, addition of these capsules to a matrix of PMMA will add a new dimension to the material's properties; the interface bonding between the capsules and PMMA must be assessed and the effects of various weight percentage amounts of capsules analyzed. Composite properties will be compared to the properties of pure PMMA and the healing capabilities assessed *in vitro*. This design of self-healing bone cement is multi-faceted, requiring us to perform detailed assessments of each phase in order to achieve success.

References:

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