Non-invasive Diagnosis of Aseptic Implant Loosening via Electrical Impedance Tomography

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INTRODUCTION: Joint replacement is one of the most common orthopaedic procedures, with over 2 million surgeries performed each year across the globe. Loss of implant fixation, or aseptic loosening, is the leading cause of revision following primary joint replacement, accounting for ~25% of all revision cases [1]. However, diagnosis of aseptic loosening and its underlying causes remains challenging due to the low sensitivity and specificity of plain radiographs. Early, cost-effective, and accurate diagnosis of implant loosening is needed to quickly identify potential problems with new implant technologies before sizeable numbers of patients are impacted. To address this, we propose a novel approach inspired by structural health monitoring (SHM) [2] involving the use of a self-sensing bone cement (i.e. by imparting deformation and/or damage-dependent electrical conductivity or piezoresistivity) combined with electrical impedance tomography (EIT). Piezoresistivity is imparted to bone cement via incorporation of a small weight fraction of micro/nanoscale conductive fillers. Mechanical effects such as loosening and/or breakage will manifest as a conductivity change of the cement. It is hypothesized that such changes can be identified by EIT. The goal of the work presented here was to computationally explore this hypothesis.

METHODS: Computational simulations were conducted to determine whether EIT combined with piezoresistive cement could be used to: 1) detect a longitudinal crack in the cement (modeled as unjoined nodes) and 2) detect axial prosthesis migration (0.1 mm) within the cement (Fig. 1). A portion of the thigh including skin, fatty tissue, and muscle, together with a femoral prosthesis affixed using bone-cement, were modeled (Fig. 1A). The cement was simulated as a composite containing 4 wt.% conductive nanofillers with a baseline electrical conductivity of 5×10-6 S/m. The conductivity values for skin (1.25×10-4 S/m), fatty tissue (3.75×10-2 S/m), muscle (0.123-0.488 S/m), bone (2×10-3-6 × 10-3 S/m), and the metal prosthesis (1×107 S/m) were obtained from literature. Conductivity imaging was conducted using 16 evenly spaced electrodes placed at mid-height around the reference geometry as shown in Fig. 1A. Deformation-induced conductivity changes were simulated by an analytical piezoresistivity model [3] calibrated with data for CNT-modified PEEK [4].

RESULTS: **Fig. 2A** shows the normalized conductivity changes across the limb (section A-A **Fig. 1A**) obtained via EIT in the absence and presence of a longitudinal crack within the bone cement. Noise was simulated at a signal-to-noise ratio of SNR = 100 dB. In the presence of a longitudinal cement crack, a distinct conductivity perturbation can be seen. Without the crack, this perturbation is absent. Note that minor conductivity fluctuations in both images are a consequence of noise. **Fig. 2B** shows a similar map of normalized change in conductivity with and without prosthesis displacement. Again, EIT can clearly capture the prosthesis displacement as indicated by the large conductivity change. These simulations concretely demonstrate the potential of utilizing self-sensing materials and EIT for non-invasive assessment of prosthesis-bone fixation interface.

DISCUSSION: The results validate the hypothesis that piezoresistive bone cement and EIT can be used to non-invasively monitor the implant-bone interface. Both the presence of a longitudinal crack and axial displacement of the prosthesis resulted in electrical conductivity changes measurable above the noise threshold. While these initial results are encouraging, the approach must be validated via physical experiments. Our current efforts are focused on fabrication of suitable piezoresistive bone cement composites and validation via testing of surrogate and cadaver bones in an EIT phantom. If successful, this approach could for the first time provide a means to study dynamic in vivo mechanics of aseptic implant loosening, leading to a paradigm shift in the clinical diagnosis, treatment, and understanding of this important clinical problem.

SIGNIFICANCE/CLINICAL RELEVANCE: The novel diagnostic technique proposed herein could enable early, cost-effective, and accurate diagnosis of implant loosening. This in turn could allow us to better understand and ultimately address the factors underlying aseptic loosening.

REFERENCES: [1] Kurtz SM et al. Int Orthop. 2011;35(12):1783-9. [2] Tallman et al. Struct. Health Monit. 2014; 14 (1): 100-109. [3] Tallman and Wang, Appl. Phys. Lett. 2013; 102. [4] Mohiuddin and Hoa, Nanoscale Res. Lett. 2011, 6 (419):1-5.

IMAGES AND TABLES: Three images and/or tables are allowed per abstract.

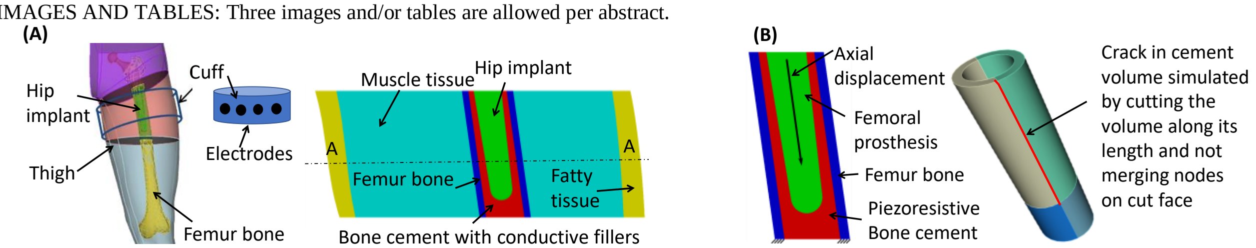

Fig. 1: (A) Schematic of human thigh with femoral prosthesis implanted using piezoresistive bone cement and an external EIT cuff to measure changes in electrical conductivity of cement due to changes in interfacial conditions. (B) Conditions simulated via computational EIT model**.**

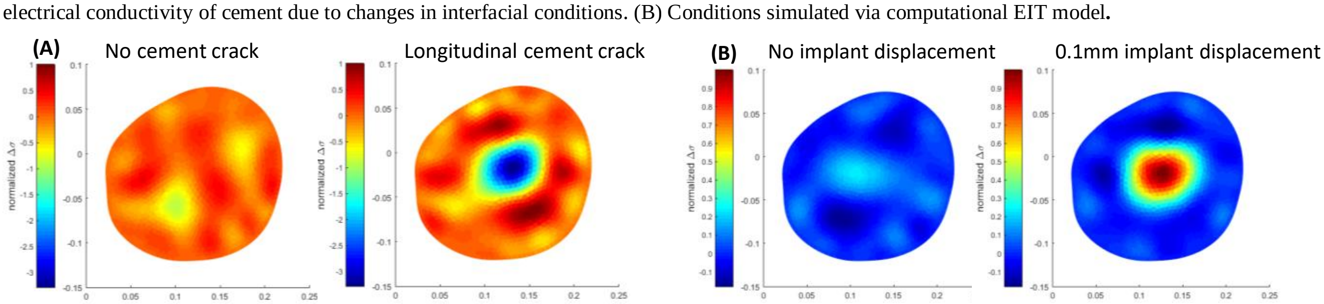

Fig. 2: Simulated map of normalized conductivity relative to baseline based on electrodes placed around cross-section A-A of Figure 1. (A) In the absence vs. presence of a crack in the bone-cement volume. (B) With and without prosthesis displacement.