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A Multiphysics Model for Radiofrequency Activation of Soft Hydrated Tissues

Zhongqing Han, Rahul, Suvranu De*

Center for Modeling, Simulation and Imaging in Medicine, Rensselaer Polytechnic Institute, 110 8th Street, Troy, NY 12180, USA

Abstract

A multi-physics model has been developed to investigate the effects of cellular level mechanisms on the electro-thermo-mechanical response of hydrated soft tissues with radiofrequency (RF) activation. A micromechanical model generates an equation of state (EOS) that provides the additional pressure arising from evaporation of intra- and extracellular water as well as temperature to the continuum level thermo-mechanical model. A level set method is used to capture the interfacial evolution of tissue damage with the level set evolution equation derived from the second law of thermodynamics, which is consistent with Griffith's fracture evolution criterion. The discretized equations are solved simultaneously using a Krylov subspace based iterative solver (GMRES) with block preconditioning that effectively deflates the spectrum of the system matrix, resulting in exponential convergence of the Arnoldi iterations. Example problems, including experimental validation, illustrate the computational accuracy and efficiency of the technique.

Keywords: Multi-physics modeling; Electrosurgery; Level set method; Equation-of-state; Preconditioning

1. Introduction

Instruments that utilize radiofrequency (RF) alternating current in the range of 300Hz-5 MHz, are increasingly being utilized to perform a variety of surgical and other therapeutic procedures [1]. RF has the advantage of dissecting tissue with simultaneous coagulation, leading to hemostasis. The frequency range precludes neuromuscular stimulation and therefore entails no risk of electrocution [2]. However, to avoid significant tissue damage and other adverse events during surgical procedures as well as to develop more effective devices and procedures, there is need to develop models that account for the effects of the biophysics of RF electricity on the thermo-mechanical response of soft tissues.

When RF electrical energy is concentrated in a very small area of the tissue the resulting high current density increases intra- and extracellular temperature due to oscillations of large protein ion in the cytosol of the cells. This leads to vaporization of water from the cells, protein denaturation, and various tissue effects including coagulation, desiccation or dehydration, and carbonization [3]. The efficacy of electrosurgical techniques depends on being able to dissect tissue locally while minimizing inadvertent thermal damage of neighboring tissue to prevent adverse surgical outcomes. The dissection or cutting mechanism is associated with continuous delivery of currents into tissue governed by Joule's law [4]. Previous studies have investigated the mechanism of explosive vaporization for creating dissections [5–7]. The "cut" mode, with its continuous delivery of current, creates higher tissue temperatures in a shorter time, leading to boiling of intra- and extracellular water and consequently cause the cell membrane to rupture, release, and evaporation of the cellular water resulting in tissue dehydration and desiccation.