Non-Fourier Heat Conduction in Soft Tissues: Experiments, Models, Waves

Abstract
Electrosurgery of soft tissue organs involves the application of a high voltage at high frequency to the interface between the surgical probe and the tissue boundary. To accomplish correct interaction of the electrosurgical probe with the tissue (i.e., coagulation of blood at the probe/tissue interface) as opposed to charring, it is imperative to understand the heat conduction phenomena due to moving heat sources. Recent research [1] has established experimental evidence for the damped-hyperbolic character of transient heat conduction – described by a Maxwell-Cattaneo (not a Fourier) model – in porcine muscle tissue and blood. A fractional derivative of order $\alpha = 0.5$ offers the most appropriate model for heat conduction in blood while an integer model is sufficient to describe heat conduction in muscle. Since the thermal signal speeds are on the order of a few millimeters per second, by way of analogies, one needs to consider subsonic ($M < 1$) and even supersonic ($M > 1$) *second sound phenomena* during electrosurgery. In 2d (resp., 3d) problems, this translates into a possible formation of Mach wedges (resp., Mach cones). The subsonic case has recently been examined in [2]. Two types of sensitivity studies of supersonic 2d problems have been performed so far: (i) non-rectilinear paths of a heat source in two-phase inhomogeneous media and (ii) rectilinear paths of heat source in random fractal media. The latter case is motivated by the widely reported fractal character of many biological tissues, while its solution relies on a methodology outlined in [3]. Both types of studies are richly illustrated by 2d computer simulations of transient heat fields.

[1] A. Madhukar, Y. Park, W. Kim, H.J., R. Berlin, L.P. Chamorro, J. Bentsman, and M. Ostoja-Starzewski, "Heat conduction in porcine muscle and blood: Experiments and time-fractional telegraph equation model," *J. Roy. Soc. Interface* **16**, 20190726, 2019.

[2] Y. Povstenko and M. Ostoja-Starzewski, "Doppler effect described by the solutions of the Cattaneo telegraph equation," *Acta Mech.* **232**, 725-740, 2021.

[3] X. Zhang and M. Ostoja-Starzewski, "Impact force and moment problems on random mass density fields with fractal and Hurst effects," in special issue "Advanced materials modelling via fractional calculus: challenges and perspectives," *Phil. Trans. Roy. Soc. A* **378**(2172), 20190591, 2020.