

THERMAL FINITE ELEMENT ANALYSIS OF OSTEOCYTE KILL ZONES ACHIEVED WITH ACRYO-INSULT PROBE

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INTRODUCTION Osteonecrosis remains a major unsolved problem in orthopaedic hip surgery, responsible for about 10% of the primary cases and 20% of the societal cost of total hip arthroplasty (Mont, 1995). To help in devising head-preserving surgeries, we have recently developed a method of creating segmental lesions by using a cryogenic probe (Reed, 2001) in the emu, a large biped which progresses to femoral head collapse (Conzemius, 2000).

In order to parametrically modulate the shape and size of the kill zone (ice ball) produced *in vivo* with the cryogenic probe, a thermal finite element model has been developed, and validated using bench-top surgical simulations. The model has been implemented to guide the intraoperative protocol to determine freezing time to achieve a specified kill-zone.

METHODS A closed-circulation cryo-insult probe, (Figure 1) previously described (Reed, 2001), consists of an outer and inner tube (15 gage and 21 gage 316 stainless steel thin-walled tubing). The outer tube is wrapped in 37 gage high-resistance heating wire, and coated with Teflon for protection. The tip of the probe is thermally isolated from the heated shaft by a small piece of Ultem (polyetherimide). Type T thermocouples are located at the tip and just above the Ultem insulator, so that shaft temperature can be controlled intraoperatively.



Figure 1: Schematic of the closed-circulation cryogenic probe

An axisymmetric thermal finite element model of this probe was developed, using Patran 9.0 for pre-processing (HKS, Pawtucket, RI), and ABAQUS 6.2 for analysis (MSC, Los Angeles, CA). The probe is surrounded by an “infinite” field of a 1% agarose-water gel (whose thermal conductivity matches that of cancellous bone) (Biyikli, 1986). Tip and shaft temperature boundary conditions consisted of curves taken directly from experimental data. Additionally, a far-field boundary condition of room temperature (or emu body temperature, for *in vivo* simulations) was imposed. Model validation consisted of comparing simulated temperature-time curves with those achieved experimentally.

There were three differences between the validation and *in vivo* models: *in vivo* simulations (1) consisted of multiple freeze-thaw cycles, (2) started at emu body temperature (instead of room temperature), and (3) included the warming effects of blood flow in the femoral head.

To simulate blood flow, all substrate (bone tissue bed) elements had a volumetric heat source,

$$q_p = \eta(T_s) \cdot \rho_p \cdot C_{p_p} \cdot \beta \cdot [T_c - T_s]$$

where: q_p = power (W/cm^3); $\eta(T_s)=1$ if $T_s > 273$ K, 0 if $T_s < 273$ K; ρ_p =blood density (g/cm^3); C_{p_p} =blood spec. heat ($J/g \cdot K$); β =blood perfusion rate ($g/g \cdot s$); T_c =element temperature (K); and T_s =body temperature (K).

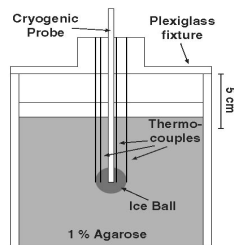


Figure 2: Experimental probe testing setup

The experimental probe testing setup (Figure 2) consisted of 5 type T thermocouples, embedded in the agarose gel at locations ranging from 0 mm to 12 mm from the cryogenic probe. Liquid nitrogen was circulated through the probe using a Cryogun (Brymill Cryogenic Systems, Ellington, CT). Data were collected using LabVIEW (National Instruments, Austin, TX).

Operator control of cryo-insult was via valve attenuation of liquid N_2 flow to the probe, rather than by probe temperature set point. Therefore, time-variant probe temperatures (recorded experimentally) were used to drive the simulation.

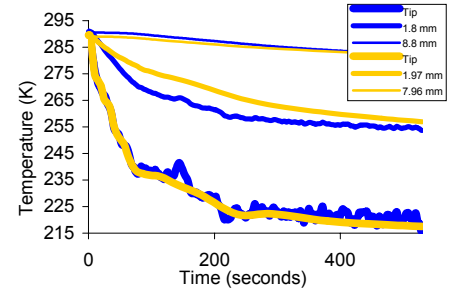


Figure 3: Comparison of experimental (dark) and FE (light) temperature histories during a 9-minute freeze

RESULTS Experimental and validation simulations showed close correspondence in temperature-time curves at various radii (figure 3), and similar ice-ball expansion rates. Validation trials were conducted for nine-minute cryo-insults (a time similar to that previously used, empirically, for emu surgeries).

In vivo freeze-thaw cycles showed a decrease in freeze-front expansion, and an increase in thaw rates, due to femoral head blood perfusion. Additionally, as expected, there was a slight increase in ice-ball radius during subsequent freezes, due to a lower “initial” temperature of the surrounding tissue (Figure 4).

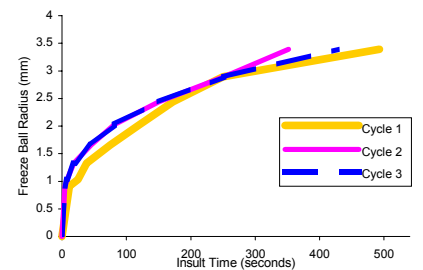


Figure 4: Computed *in vivo* ice ball radii for three consecutive nine-minute freeze-thaw cycles

DISCUSSION

This validated FE model has proven invaluable as a means to predictably modulate lesion sizes for our *in vivo* emu surgeries.

SUMMARY A finite element model describing the temperature fields surrounding a cryogenic probe has been developed and validated. This model has been used to estimate the temperature history of bony tissue during local surgical freezing, for the purpose of creating osteonecrotic lesions.

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