Simulation Based Design of Scalp Cooling Systems to Prevent Chemotherapy-Induced Alopecia

Bradley Pliskow, Kunal Mitra, P.h.D, Mehmet Kaya, P.h.D.
Florida Institute of Technology, Melbourne, FL

Introduction: Alopecia continues to be one of the most distressing and traumatic side effects for patients undergoing chemotherapy treatment. Scalp cooling was introduced in the 1970's as a method of reducing or preventing chemotherapy-induced alopecia. The type or design of the cooling device for this procedure is an important factor that has not been thoroughly studied. Modeling of heat transfer within the human head may provide insight into various aspects of scalp cooling device design. Previously, a numerical model was developed to study the scalp cooling procedure by quantifying the relationship between temperature and perfusion in the scalp. In the present work, a numerical model is developed with a focus on the cooling device.

Materials and Methods: A numerical model of heat transfer is developed in Comsol Multiphysics software to simulate the interaction of various types of cooling caps with the human head. The head geometry is created as a half-ellipsoid in 3-D space based upon the head sizes from NIOSH Anthropometric Data and ISO Digital Headforms. The head tissue is divided into different, homogenous layers, each represented using thermo-physical properties according to literature values. Penne's bio-heat equation is used as a continuum approach to describe heat transfer within human tissue with temperature-dependent blood perfusion and metabolic heat generation.

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot k\nabla T + \rho_b c_b \omega_b (T_A - T) + q_m \quad (1)$$

Unlike previous models, the Bio-heat equation is not used to govern heat transfer within the cooling cap. Rather, a separate differential equation is used, namely the heat equation. Depending on the type of cap being simulated, the heat equation can be applied appropriately. For a liquid-cooled cap, the Navier-Stokes equation is solved to calculate the fluid velocity field. For a solid cap, the velocity field is zero and the heat equation is simplified accordingly. In this work, pre-cooled and liquid-cooled cap designs are simulated using the model.

Results and Discussion: The model is utilized to simulate the simultaneous cooling of the tissue and warming of the cap after application of a pre-cooled cap initially at -20°C (Figure 1).

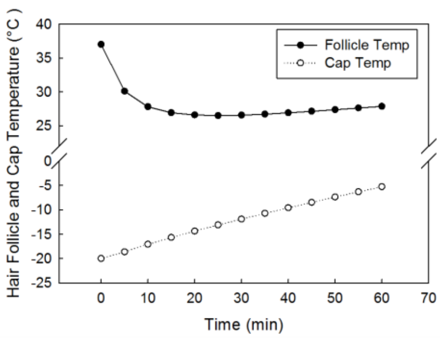

Figure 1. Transient temperature response after application of a pre-cooled cap with initial temperature of -20°C. The tissue temperature at the depth of the hair follicle and the temperature of the cap are simulated over time.

The hair follicle (subcutaneous depth 2 mm) reaches a minimum temperature of 26.9°C approximately 25 minutes after application of the cap. This suggests that a pre-infusion cooling time of 20-25 minutes should be used for a pre-cooled cap. After approximately 30 minutes, the hair follicle temperature begins to rise again, confirming the necessity to exchange pre-cooled caps every 30-45 minutes. The initial temperature of the cap affects the temperature of the tissue; the hair follicle temperature is nearly 25°C and 29°C for an initial cap temperature of -30°C and -10°C, respectively. Similar analyses (not presented for brevity) are conducted to simulate variation of operating parameters for a liquid-cooled cap. Additionally, variation of patient-specific parameters confirms the large impact of parameter choices for the hair/air layer thickness and thermal conductivity.

Conclusions: The modeling tools developed here provide a powerful platform for analyzing the effect of operating parameters for different scalp cooling techniques. Future studies using this model can consider other implementations of cooling devices such as convective air-cooling. Furthermore, the numerical model results should be correlated with experimental data as an effort to determine the optimal parameter choices for modeling the thermal resistance of the hair/air layer.