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# Thermal modelling of controlled scalp hypothermia using a thermoelectric cooling cap

Mark Baldry, Victoria Timchenko, Chris Menictas*

*School of Mechanical and Manufacturing Engineering, University of New South Wales, Kensington 2033, NSW, Australia*

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ABSTRACT

This study presents a novel, thermoelectric cryotherapy cap that aims to provide effective and controlled scalp cooling to prevent hair loss for chemotherapy patients. The cap's design consists of multiple thermoelectric coolers (TECs) evenly spaced and bonded to a soft thermal interface material, tightly fitted to a patient's head. A numerical model is developed to assess the performance of alternative cap designs in relation to their ability to achieve hair follicle hypothermia. Under ideal conditions, 26.5 W of heat removal from the scalp is required to achieve the clinically-significant follicle temperature target of 22 °C. Temperature maps of the subcutaneous tissue are generated to visualise the development of hypothermic follicles, and thereby assess the effectiveness of the cap design. Transient studies show that cooling to the therapeutic temperature can be achieved within 40 min. To avoid the possibility of cold-induced tissue damage, individual thermoelectric cooling modules should not be operated at a cooling flux beyond approximately 3175 W/m$^2$. This may be achieved with 38 modules evenly spaced in a checkerboard arrangement, each providing 0.7 W of cooling to the scalp.

## 1. Introduction

Chemotherapy-induced alopecia (CIA) is a distressing side effect of chemotherapy treatment (Kargar et al., 2011; Lemenager et al., 1997; Lemieux et al., 2009; Schaffrin-Nabe et al., 2015). Scalp cooling was introduced in the 1970's as a way to limit or inhibit CIA (Edelstyn and MacRae, 1977; Pliskow et al., 2016). The basis of this method is that reduction of the temperature of the hair follicle tissue (approximately 1–2 mm below the surface) below 22 °C supresses metabolic activity and trigger vasoconstriction of the blood vessels supplying these cells (Belum et al., 2016; Gregory et al., 1982; Janssen et al., 2005a, 2005b; Lemenager et al., 1997; Pliskow et al., 2016; Rugo et al., 2017). These two mechanisms combine to reduce the local uptake of chemotherapy drugs, thereby minimising hair follicle damage or death (Grevelman and Breed, 2005; Janssen et al., 2007; Kargar et al., 2011).

As it is very difficult to directly measure the thermal gradient within a patient's head during scalp cooling treatment, this procedure is often neglected (Grevelman and Breed, 2005; Lemenager et al., 1997). Localised tissue cooling must be controlled to balance the need to achieve the aim of cryotherapy (in this case CIA prevention) against the risk of cold-induced tissue damage (Khoshnevis et al., 2016). Numerical models have been used to estimate the subcutaneous temperature profile and circumvent the need for direct measurement (Cojocaru et al., 2016; Gregory et al., 1982; Janssen et al., 2007, 2009, 2005a, 2005b; Keller et al., 2009; Lin et al., 2017; Neimark et al., 2008; Nunneley, 1998; Pliskow et al., 2016; Sukstanskii and Yablonskiy, 2007; Van Leeuwen et al., 2000). Whilst there is a very large body of published literature focussing on the clinical and experimental development of scalp cryotherapy, there are few numerical studies. Early work targeted selective brain cooling via the head and neck in both adults and infants (Nunneley, 1998; Van Leeuwen et al., 2000; Zhu and Diao, 2001). These studies mostly used spherical geometries with simple layer structures, but provided the foundation for modelling head cryotherapy with Pennes' bioheat model. They also collated and assessed a range of essential model parameters, such as metabolic heat production and blood perfusion. The work by van Leeuwen et al. (2000) was particularly salient for this area of study, as the authors validated Pennes' bioheat model against a model including complex, discrete vasculature based on MRI scans of patient's heads, thereby improving confidence in the simplified approach. Additional work centred on selective brain cooling has shown that the presence of cerebrospinal fluid may influence heat transfer through the head (Sukstanskii and Yablonskiy, 2007). The thermal resistance between the external hair boundary and the cooling device has also been identified as a critical factor in ensuring adequate subcutaneous heat removal, especially for deeper tissue (Neimark et al., 2008; Sukstanskii and Yablonskiy, 2007). Work by Keller et al. (2009) suggests that the placement of the cooling device on the head or neck may influence the success of brain cooling,

* Corresponding author.
*E-mail address:* c.menictas@unsw.edu.au (C. Menictas).

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**Nomenclature**

***Term significance***

| | |
|---|---|
| CIA | Chemotherapy-induced alopecia |
| $C_p$ | Heat capacity at constant pressure [J/kg K] |
| $\Delta T_{max}$ | Maximum temperature difference achievable across TEC [K] |
| ε | Material emissivity |
| h | Boundary surface heat transfer coefficient [W/m$^2$ K] |
| $I_{max}$ | Current draw at Qmax [A] |
| k | Thermal conductivity [W/m K] |
| **n** | Outward pointing normal vector |
| φ | Scaling factor for van't hoff effect |
| **q** | Conductive heat flux [W/m$^2$] |
| $Q_{10}$ | Van't hoff factor |
| $Q_c$ | TEC cooling rate [W] |
| $Q_m$ | Metabolic heat generation rate [J/m$^3$] |
| $Q_{max}$ | Maximum cooling possible [W] |
| $q_c$ | Boundary heat removal [W/m$^2$] |
| ρ | Density [kg/m$^3$] |
| σ | Stefan-Boltzmann constant |
| T | Temperature [K] |
| TEC | Thermoelectric Cooler |
| Θ | Volume fraction in porous medium |
| TIM | Thermal interface material |
| **u** | Fluid velocity field [m/s] |
| $V_{max}$ | Voltage across TEC at Qmax [V] |
| ω | Blood perfusion [1/s] |

***Subscript significance***

| | |
|---|---|
| amb | Ambient property |
| b | Blood |
| eff | Effective property accounting for both solid and fluid properties in porous matrix |
| 0 | Property measured at thermoneutral conditions |
| s | Solid |

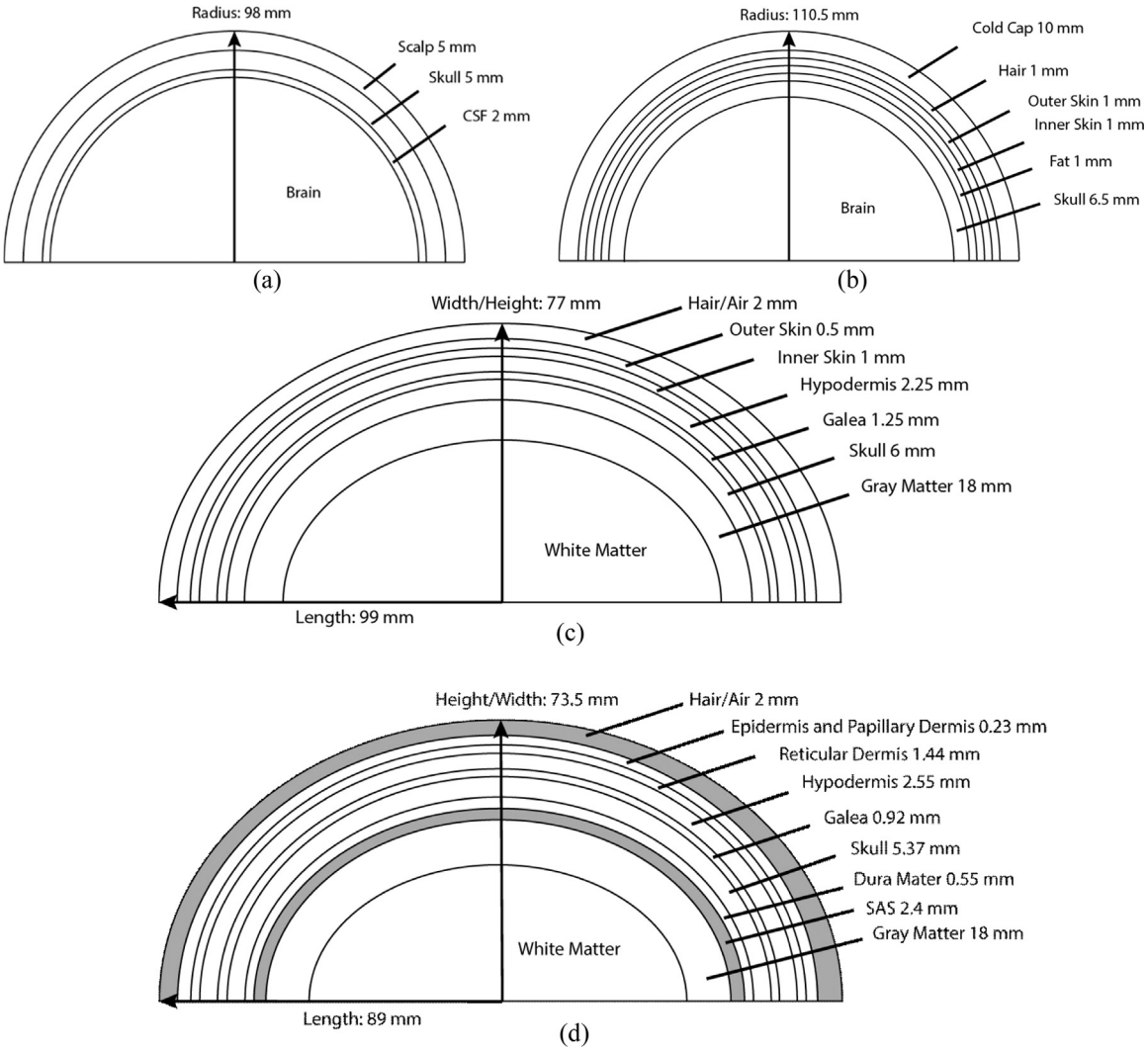


**Fig. 1.** Various head geometries reproduced based on previously published figures in (a) Nelson et al. (1998), (b) Janssen et al. (2005a, 2005b), (c) Pliskow et al. (2016), (d) proposed configuration in the current work. SAS stands for 'sub-arachnoid space'. Grey shaded regions indicate porous media zones. Images produced by the current author with Adobe Illustrator based on dimensions reported in the literature.