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An experimental study and finite element modeling of head and neck cooling for brain hypothermia

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ABSTRACT

Reducing brain temperature by head and neck cooling is likely to be the protective treatment for humans when subjects to sudden cardiac arrest. This study develops the experimental validation model and finite element modeling (FEM) to study the head and neck cooling separately, which can induce therapeutic hypothermia focused on the brain. Anatomically accurate geometries based on CT images of the skull and carotid artery are utilized to find the 3D geometry for FEM to analyze the temperature distributions and 3D-printing to build the physical model for experiment. The results show that FEM predicted and experimentally measured temperatures have good agreement, which can be used to predict the temporal and spatial temperature distributions of the tissue and blood during the head and neck cooling process. Effects of boundary condition, perfusion, blood flow rate, and size of cooling area are studied. For head cooling, the cooling penetration depth is greatly depending on the blood perfusion in the brain. In the normal blood flow condition, the neck internal carotid artery temperature is decreased only by about 0.13 °C after 60 min of hypothermia. In an ischemic (low blood flow rate) condition, such temperature can be decreased by about 1.0 °C. In conclusion, decreasing the blood perfusion and metabolic reduction factor could be more beneficial to cool the core zone. The results also suggest that more SBC researches should be explored, such as the optimization of simulation and experimental models, and to perform the experiment on human subjects.

1. Introduction

Therapeutic hypothermia is a treatment method for sudden cardiac arrest (SCA) to prevent physical brain injury from cerebral ischemia (Bernard et al., 2002; Gwinnutt and Nolan, 2003; Zviman et al., 2004) and reduce systemic neurological damage (Yenari and Han, 2012; Kim et al., 2014). SCA is characterized by the sudden circulatory collapse caused by a cardiac arrhythmia. The timely and effective treatment for SCA is challenging. Nearly 20% of all mortality in industrialized countries is due to SCA (Josephson, 2014), which is the leading cause of death among adults in the US (McNally and Valderrama, 2011) with about 180,000 to 450,000 incidences annually (Kong et al., 2011). SCA causes the brain to become oxygen deprived and ischemic, and leads to permanent damage to brain tissue in minutes if not treated (Terpolilli et al., 2012). The longer the brain suffers from oxygen deprivation and ischemia, the more damage is caused. It is critical to start the treatment as early as possible given the limited therapeutic time window (Kammersgaard et al., 2000). However, about two thirds of SCA cases occur outside of a hospital (McNally and Valderrama, 2011), making it difficult to provide timely treatment to SCA patients.

Therapeutic hypothermia can be induced in the field by intravenous infusion (Bernard et al., 2003), surface cooling with ice packs (Bernard et al., 1997), forced cold air cooling (Nikolov and Cunningham, 2003), or endovascular devices (Guluma et al., 2006). It complements other SCA treatment methods, including cardiopulmonary resuscitation (CPR) (Pierce et al., 2015), drug therapy (Jacobs et al., 2011), surface cooling blankets (Merchant et al., 2006) and defibrillation (Girotra et al., 2012). During therapeutic hypothermia, experts recommend decreasing the whole body temperature to 32–34 °C for 12–24 h after return of spontaneous circulation (Peberdy et al., 2010). When brain temperature is decreased by 1 °C, cerebral oxygen consumption rate is reduced by 5%, thus increasing tolerance to ischemic conditions and

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Table 1
Clinical application on selective brain cooling.

Cooling methods	Subjects	Temperature of cooling media	Cooling time	Key findings	Reference
Head and neck cooling garment	12 female and 12 male subjects (age 25–55 years)	< 10 °C	30 min	Oral temperatures decreased approximately 0.2–0.6 °C	(Ku et al., 1996)
Cooling helmet	14 patients	–	60 min	0.8 cm below the cortical surface decrease 1.8 °C (range 0.9–2.4 °C)	(Wang et al., 2004)
Head and neck cooling device	11 patients	4 °C	60 min	> 3 cm below the cortical surface decrease 0.3 °C	(Poli et al., 2013b)
Head and neck cooling device	10 healthy men (age 35 ± 13 years)	4 °C	120 min	Forehead skin temperature dropped by 5.5–2.2 °C; tympanic temperature decreased by 4.7–0.7 °C	(Koehn et al., 2012b)
Head and neck cooling device	10 healthy volunteers	4 °C	190 min	Tympanic temperature drop to 34.7 °C	(Kallmunzer et al., 2011)
Intranasal balloon catheters	10 awake volunteers	20 °C	60 min	−1.7 ± 0.8 °C drop in brain by MRI	(Covaciu et al., 2011)

extending the therapeutic time window (Hägerdal et al., 1975). The neurological outcome can be improved if therapeutic hypothermia was started during the CPR (Cronberg et al., 2009; Debaty et al., 2014). When the whole body is cooled by 3–5 °C during therapeutic hypothermia, strong shivering may occur in response to the temperature drop and cause the body to rewarm. This may worsen the ischemic conditions as a result of increased oxygen consumption (Esposito et al., 2014). Selective brain cooling (SBC), wherein the temperature of brain is reduced without lowering the whole body temperature, has been utilized as a potentially effective strategy for patients suffering from SCA (Benson et al., 1959). SBC may achieve similar neuroprotection while causing fewer systemic effects in comparison to whole body cooling (Laptook et al., 1997).

Head and neck cooling, the subject of this research, are important parts of the SBC procedure to lower the temperature of the brain. As summarized in Table 1, past studies include using the head and neck cooling garment (Ku et al., 1996), cooling device with iced water (Wang et al., 2004) or other cooling media (Kallmunzer et al., 2011; Koehn et al., 2012b; Poli et al., 2013b), and intranasal cooling (Covaciu et al., 2011). Ku et al. (1996) studied the cooling garment (Mark VII by Life Support Systems, Mountain View, CA), which circulates the mixture of propylene glycol and water, with inflatable air bladders to ensure good contact with skin. Wang et al. (2004) developed a nylon fabric helmet, which consisted of two internal layers for cold water and pressurized air, to reduce the head temperature via heat conduction. Poli et al. (2013b) and Koehn et al. (2012b) utilized a head and neck cooling device (Sovika by HVM Medical, Rotenburg, Germany) which has cold fluid (4 °C) running through the internal channels of the helmet. Cooling is achieved via heat conduction between the helmet and skin of the head and neck. Kallmunzer et al. (2011) evaluated a free-floating cooling gel based helmet, which covers the head with the exception of the face. Covaciu et al. (2011) investigated intranasal cooling balloons with circulated cold saline on human volunteers and used magnetic resonance imaging (MRI) to measure temperatures inside the brain.

Other than MRI, it is challenging to measure brain temperatures, making it difficult to evaluate the efficacy of SBC. Experimental phantom model and numerical simulation approaches provide two alternative ways to validate the numerical simulation and evaluate the efficacy of SBC with more insightful information about temporal and spatial temperature distributions. Previous studies on numerical simulation of SBC have investigated hypothermia via head (Zhu and Diao, 2001; Zhu and Rosengart, 2008), neck (Bommadevara and Zhu, 2002), head and neck (Keller et al., 2009), and torso (Smith and Zhu, 2010a, 2010b). Zhu and Diao (2001) investigated cooling on adult and infant models via cold fluid or ice pack around the head and found a temperature gradient of up to 13 °C in the brain. Zhu et al. (Zhu and Rosengart, 2008) also used miniature cooling probes directly inserting into injured brain tissue, but cooling penetration was limited to 10 mm in axial direction and 19 mm in laterally direction around the cooling probe. Eginton (2007) presented the blood vessels and structures as straight tubes in the neck cylinder and found the temperature drop for the internal carotid artery was 0.7 °C in one hour. Bommadevara and Zhu (2002) developed a vascular heat transfer model to simulate temperature decrease along the carotid artery in humans. It was found that a 1.1 °C temperature drop along the carotid arteries was possible when the neck surface was cooled to 0 °C using the cooling helmet. Keller et al. (2009) studied a hypothermia model based on the cooling cap together with a 6 °C cooling neckband. Smith and Zhu (2010a, 2010b) presented the torso-cooling pad through temperature reduction of spinal fluid for brain hypothermia. Results showed that the average grey matter temperature decreased to 35.4 °C while cooling on white matter was limited.

Although numerical and experimental methods have been conducted to investigate brain cooling, there are still needs to understand temperature distributions in the head and neck to validate the efficacy