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Effect of Heat on Wounded Warriors in Ground Combat Vehicles: Insights from the Army Medical Community, and the Simulation of a Novel Method for Soldier Thermal Control

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- Wounded warriors are generally less tolerant to the effects of heat.
- Because injuries often degrade thermoregulatory capability, the outcome for wounded warriors is especially affected by severe thermal conditions.
- Severe thermal conditions can exist within ground combat vehicles; although these vehicles are generally equipped with heating, ventilation, and cooling (HVAC) systems, the HVAC systems often lack sufficient cooling capacity under conditions of thermally severe weather, open-hatch operations, and significant amounts of on-board electronics.
- The effect of heat on wounded warriors within ground combat vehicles is considered by:
 - Providing insights gleaned from the Army medical community
 - Simulating a novel method for soldier thermal control



Insights from the Army Medical Community

Casualty Types



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- Original Scope:
 - Generally: (1) the type / severity of the casualty, (2) the frequency of the casualty on the battlefield, (3) criticality with respect to the life of the soldier, and (4) thermoregulatory significance.
 - Specifically: (1) heat (exhaustion and stroke), (2) ballistic (blunt and penetrating / perforating), (3) pressure / blast (limb loss, paralysis, organ rupture), and (4) burn.
- However, physiological and or thermoregulatory data associated with such injuries is generally not readily available. Therefore, the simulation study was generally limited to healthy soldiers, but soldiers suffering from heat injury were considered as well.
 - Heat injuries represent a significant problem on the battlefield and in training.
 - In 2005, 1,700 heat injuries occurred in the U.S. Army, with the incidence rate of heat stroke in particular increasing from 1.8 per 100,000 soldiers in 1980 to 14.5 per 100,000 soldiers in 2002.
 - With ongoing operations in Iraq, Afghanistan, and other hot climates, the heat injury rates seem unlikely to significantly drop soon.



Insights from the Army Medical Community

Casualty Care Equipment (1 of 2)



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- **Medical Vehicle HVAC:**
Generally insufficient as it relates to air cleanliness, humidity, ventilation, and temperature
- **Patient Litter:**
 - It must be transported along with the patient; therefore, it ought to be light, easily movable, robust, and cleanable
 - These desired litter characteristics tend to preclude incorporation of thermal control

- Casualty Covering
 - The casualty covering could range from a simple blanket to a sophisticated thermal garment.
 - The standard issue blanket is made of wool, and has been noted to not be very effective.
 - Mylar blankets, due to their highly insulative characteristics, have been used to assist in thermoregulation for casualties with low core temperatures.
 - For casualties with elevated core temperatures, a thermal garment or blanket can be used to provide active cooling; the garment or blanket can be air- or liquid-cooled.



Insights from the Army Medical Community

Casualty Care Controversy (1 of 3)



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- Because most ground medical vehicles shuttle casualties, the casualties generally ought to be stable.
- Traditionally, the guidance has been to keep casualties warm, based on the following rationale:
 - Many trauma injuries involve blood loss, which is generally attended by a decrease in core temperature.
 - Sufficiently reduced core temperature is generally associated with coagulopathy – detrimental to bleeding casualties because of the associated hindrance of wound blood clotting.
 - Multiple studies conclude that hypothermia, especially unregulated hypothermia, is harmful for trauma casualties.
 - Along with acidosis and coagulopathy, hypothermia is a member of the “deadly triad” which marks patients as being near the end of their physiologic reserve.

- However, there also could be benefits associated with not warming the casualties (reduced core temperature):
 - The body's thermoregulatory system naturally tends to shunt blood flow to the body core via peripheral vasoconstriction, thus potentially decreasing peripheral blood loss.
 - For normal subjects, skin blood flow can range as a percentage of cardiac output from nearly about 5% for normothermic conditions to as much as 60% for maximum heat stress caused vasodilation.
 - Such vasodilation puts greater strain on the heart, and generally augments the injury-related cardiovascular problems.
 - Resulting decrease of metabolic activity (and respiratory and cardiac activity) as well as blood perfusion needs.
 - Because casualties are often characterized by significant blood loss, the effects of a decreased core temperature may be beneficial.
 - The use of intentional hypothermia during surgery for the purpose of tissue preservation and reduction of blood flow and oxygenation needs is well established.




Insights from the Army Medical Community

Casualty Care Controversy (3 of 3)



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- Regarding this ongoing controversy associated with the ideal thermal state for casualties, it can be said that a near-normothermic state should be the goal.
- The thermal state of casualties is probably best assessed via the body's core temperature; probably the best metric for core temperature, all things considered, is the rectal temperature.
 - However, monitoring of core temperature within a medical vehicle is generally not performed or possible.
 - Perhaps the measurement of rectal temperature within medical vehicles could become standard practice, given the importance of awareness of the casualty's thermal state to the treatment approach and the casualty's recovery.




Insights from the Army Medical Community

Casualty Care Challenge (1 of 2)



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- The availability of electrical power on vehicles is often in high demand and always limited; therefore, the use of power to provide cooling for wounded warriors or heat-affected soldiers ought to be efficient.
- The most efficient way of cooling: microclimate (direct) cooling
 - Unfortunately, surface cooling can cause cutaneous vasoconstriction, which increases the insulation of the soldier, thereby making cooling less efficient.
 - This vasoconstriction generally begins at skin temperatures between 32 and 33 degrees Celsius.
- However, the intermittent application of cooling to warm, vasodilated skin has been found to decrease these insulative effects of vasoconstriction.
- The optimal skin temperature range within which vasoconstriction is minimized – in such a way that thermoregulatory and cardiovascular strain are not significantly increased, and the required power is decreased – was determined to be between 33 and 35 degrees Celsius.



Insights from the Army Medical Community

Casualty Care Challenge (2 of 2)



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- A patent was obtained for a cooling / heating method using this same temperature range for skin temperature feedback control.
- Cooling is only applied when the skin temperature has surpassed the range upper limit and, subsequently, has not yet dipped to the range lower limit.
- Compared with constant cooling, the skin temperature feedback method was found to allow a 46% reduction in cooling power requirements.
- It was also found that such intermittent cooling methods require a smaller amount of body surface area for cooling, and that the time period or frequency associated with the intermittent cooling did not significantly affect the cooling performance.
- For wounded warriors, a skin temperature range between 30 and 33 degrees Celsius was deemed optimal. While this range may require more cooling and electrical power, the health benefits to the wounded warrior would be greater.

- Various tools exist which facilitate the modeling and simulation of the human body from a thermoregulation perspective:
 - Thermoanalytics' Human Comfort module used together with its RadTherm solver
 - P+Z Engineering's Fiala-FE module used together with its Theseus-FE solver
- Fiala's active and passive models comprise the segmental thermo-physical predictive capability for these tools



Insights from the Army Medical Community

Casualty Simulation -- Modeling



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- There is insufficient understanding to model the relative changes of thermoregulation mechanisms for injured soldiers relative to healthy soldiers for any type or severity of battlefield injury.
- However, “a comprehensive model ... is both laborious and expensive, but very much needed”. This kind of modeling would require “formulating a de novo model based on sub-human data (archival or actual experimentation) and simulating such responses on the human”.
- In the absence of appropriate data, it would be safe to say that “any modeling of thermoregulatory control and injury would be misdirected”.
- It was also stated that Fiala’s passive and active models were “not designed to answer the ballistic, pressure, and burn consequences”.
- A model of military working dogs which was developed by Dr. Larry Berglund at the U.S. Army Research Institute of Environmental Medicine (ARIEM) could be leveraged for such purposes, as well as rat models.



Simulation of a Novel Method for Soldier Thermal Control


Simulation Scenario (1 of 3)

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- Thermal Environment:
 - High solar loading of 1,120 W/m² (no cloud cover)
 - Effective sky temperature of 20°C
 - Hot ambient air temperature of 54.4°C (130°F)
 - Vehicle headwind speed of 2.23 m/s (5.0 mph)
 - Steady-state conditions
- Ground Combat Vehicle -- Caiman medical vehicle:
 - Both the interior and exterior flow / thermal conditions of the vehicle were simulated under steady-state conditions.
 - The vehicle was modeled as moving at a speed of 20 mph.
 - The focus of the study was the vehicle interior, and so the vehicle's mobility characteristics are not presented here.
 - To force severe thermal conditions inside the vehicle, reduced HVAC performance was simulated.



Simulation of a Novel Method for Soldier Thermal Control

Simulation Scenario (2 of 3)



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- HVAC System:
 - Front unit:
 - Recirculates air at a rate of 413 ft³/min (no fresh air intake)
 - Rejects only 500W of thermal energy
 - Rear unit:
 - Recirculates air at a rate 613 ft³/min
 - Intakes fresh air from ambient at a rate of 211 ft³/min
 - Rejects only 1,500W of thermal energy
- Patients:
 - Four patient litters in the rear of the vehicle: an upper and lower litter on either side, left and right, of the central vehicle aisle
 - Because of the lack of wounded warrior data, the patients are assumed to be healthy with normal thermoregulation capability, and generally starting with a normal core body temperature

Simulation of a Novel Method for Soldier Thermal Control

Simulation Scenario (3 of 3)

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- Cooling Garments:
 - Modeled as cooling pads wrapped around the soldiers torso and thighs, from just above the knees up to the neck (excluding the arms but including the shoulders)
 - Probably a more effective cooling scenario would involve a cooled pad on which the soldiers lie, with cool air blown between the patient and a covering
 - Clothing characteristics:
 - Thermal resistance of approximately $0.069 \text{ m}^2\text{-K/W}$
 - Evaporative resistance of $0.014 \text{ m}^2\text{-kPa/W}$
 - Clothing area factor of 1.28
 - Clothing insulation of 0.45 clo
 - Vapor permeation efficiency of 0.3
 - Cooling rate: 540W – high because of the severe thermal conditions modeled – was used for each patient
 - For the skin temperature feedback method, temperature measurement was performed for only the cooled skin

Simulation of a Novel Method for Soldier Thermal Control

Simulation Methodology (1 of 3)

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- Solving Process:
 - (1) Steady-state solution, with the thermal state of the soldiers' bodies (but not their clothing ensembles) being fixed at normothermic conditions; solving of the flow / temperature fields inside / outside the vehicle:
 - Iterative solving between a thermal solver, MuSES v.10.3.0, and a CFD solver, Star-CCM+ v.7.02.008 performed
 - Two CFD models were generated: one involving the exterior flow and the other involving the interior flow
 - Heat transfer coefficient and flow reference temperature data were passed from the CFD solver to the thermal solver, and wall temperatures were passed from the thermal solver to the CFD solver; this was performed until solution convergence was obtained
 - A script which facilitated the data passing and the iterative solving was used
 - (2) Transient solution (subsequently), with the soldiers being able to thermally respond to their surroundings, both passively and actively (via thermoregulation)



Simulation of a Novel Method for Soldier Thermal Control

Simulation Methodology (2 of 3)



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- Main Metrics (used to assess the effect of heat on wounded warriors):
 - Skin temperature
 - Skin blood flow and vasomotion
 - Cardiac output (the volumetric flowrate of blood from the heart)
- Parameters -- Soldier Thermal Conditions:
 - Thermal boundary conditions: involve the thermal characteristics of the surroundings associated with each soldier individually, including the local convection and radiation heat transfer characteristics
 - Thermal initial conditions: involve the thermal characteristics of the beginning (initial) state of the soldiers.

Simulation of a Novel Method for Soldier Thermal Control

Simulation Methodology (3 of 3)

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- Parameters -- Soldier Thermal Control:
 - Cooling control types:
 - No cooling
 - Skin-temperature feedback (STF) control
 - When the skin temperature surpasses the upper set point, cooling is applied until the skin temperature dips below the lower set point
 - As the temperature rises and again surpasses the upper set point, cooling is applied again until the temperature dips below the lower set point (and so on)
 - A script which accomplishes the skin temperature feedback cooling control was developed and implemented into the thermal model
 - Cooling control set points (for the STF control):
 - “Low cooling” range: from 33°C to 35°C
 - “High cooling” range: from 30°C to 33°C

Simulation of a Novel Method for Soldier Thermal Control

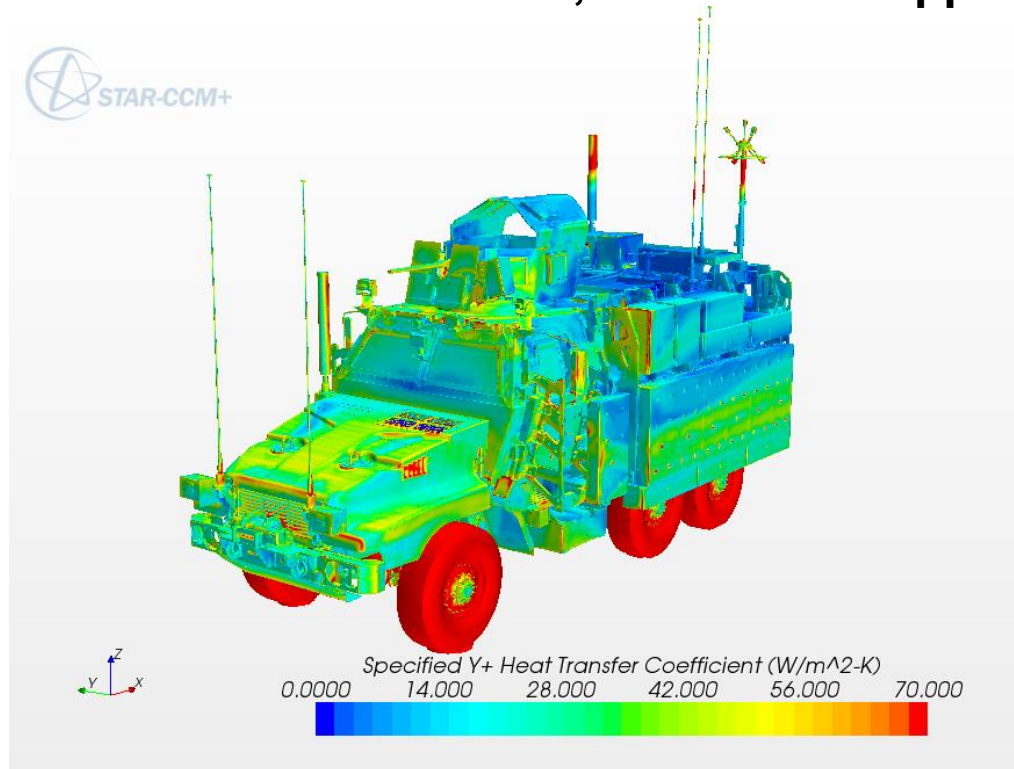
Simulation Results – Steady-State (1 of 4)

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Heat Transfer Coefficients from CFD Model, Which Are Mapped to Thermal Model:



Higher heat transfer coefficient regions include the spinning wheels and vehicle leading edges; lower heat transfer coefficient regions include the roof area over which the main flow separated because of the gunner assembly, as well as the vehicle rear exposed to the vehicle wake.

Simulation of a Novel Method for Soldier Thermal Control

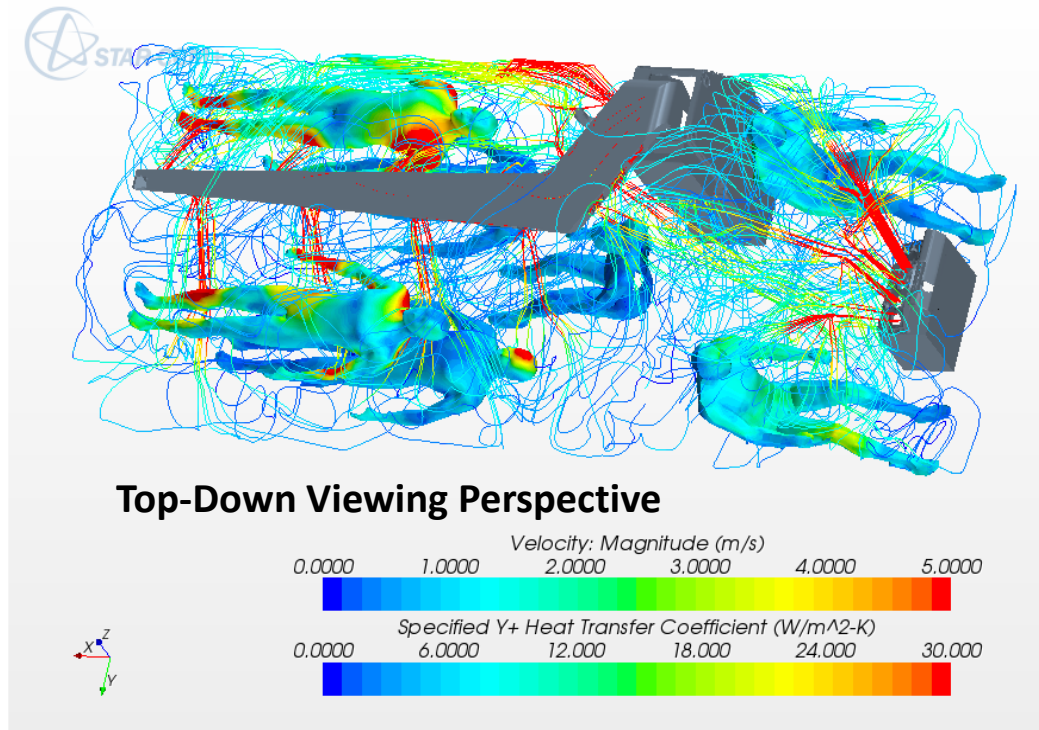
Simulation Results – Steady-State (2 of 4)

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Effect of Vehicle HVAC Flow on Soldier Heat Transfer Coefficients:



Surfaces closer to the HVAC outlet flow are characterized by higher heat transfer coefficients, increasing the thermal variability of the patients.

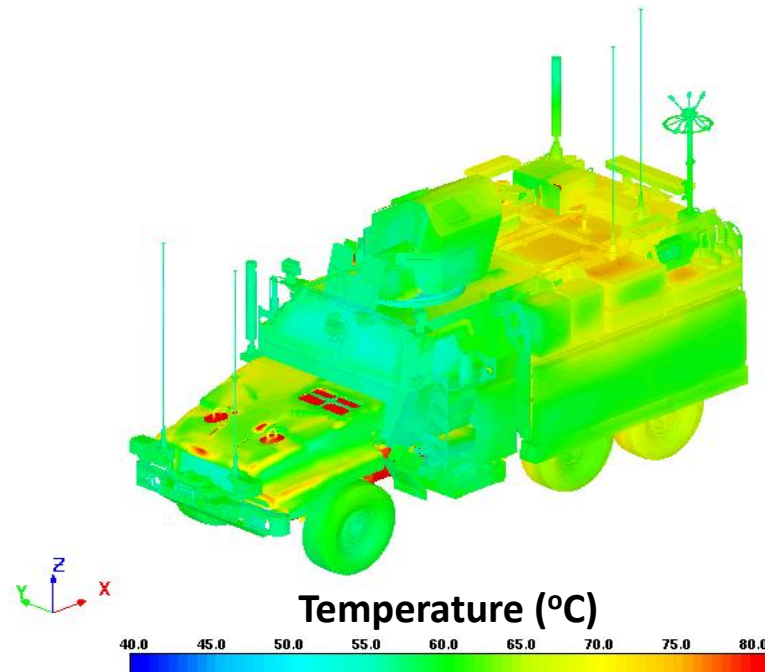
Simulation of a Novel Method for Soldier Thermal Control

Simulation Results – Steady-State (3 of 4)

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Wall Temperatures from Thermal Model, Which Are Mapped to CFD Model:



Higher temperature regions include the engine compartment, as well as the flow-separated, solar-exposed roof region near which roof-mounted electronics cooling fan flow is exhausted.

Simulation of a Novel Method for Soldier Thermal Control

Simulation Results – Steady-State (4 of 4)

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Variation of the Thermal Conditions of the Patients' Surroundings:

Patient Location	"Whole Body" Heat Transfer Coefficients (W/m ² -°C)	
	Radiative	Convective
Top-Left	5.45	36.9
Top-Right	5.42	36.9
Bottom-Left	5.28	30.8
Bottom-Right	5.22	30.6

The higher patients, because of their closer proximity to the HVAC flow outlets, are characterized by higher "whole body" heat transfer coefficients as reported by MuSES' Human Thermal Module.

Simulation of a Novel Method for Soldier Thermal Control

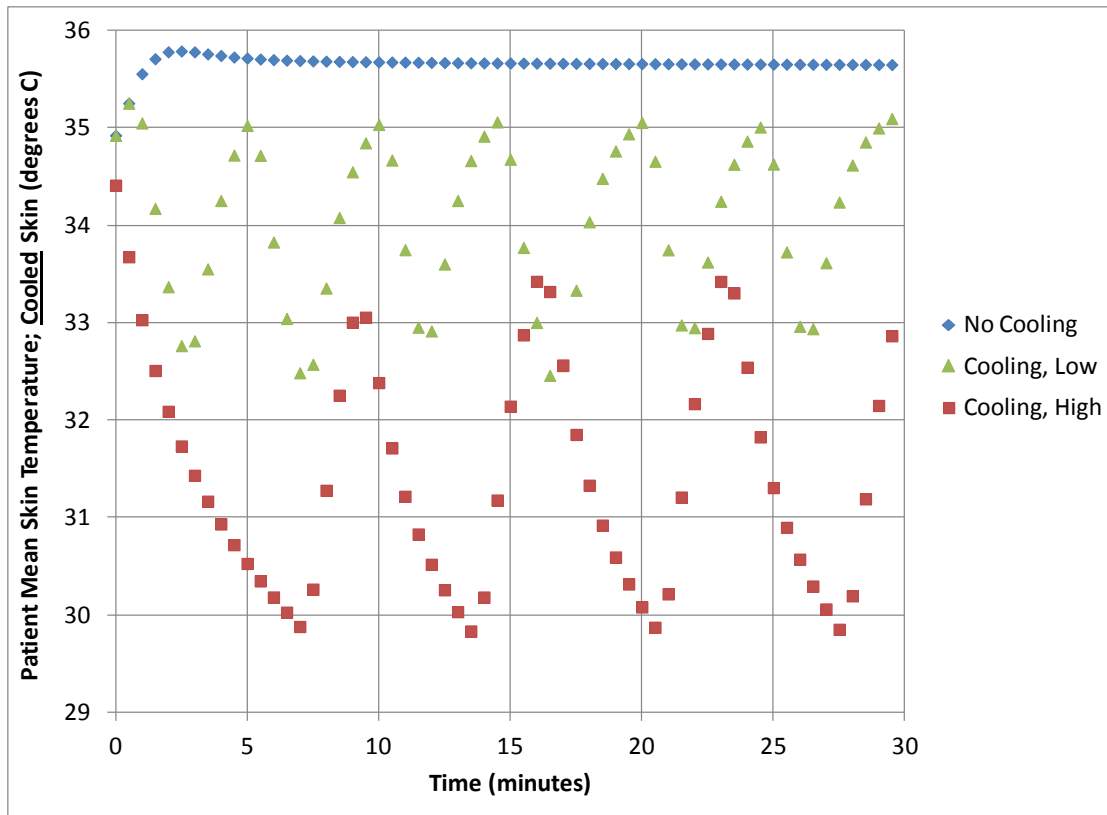
Simulation Results – Transient (1 of 5)

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Effect of Cooling Method on the Mean Temperature of the Patient's Cooled Skin:



Both cooling methods stay within their respective set points.

Simulation of a Novel Method for Soldier Thermal Control

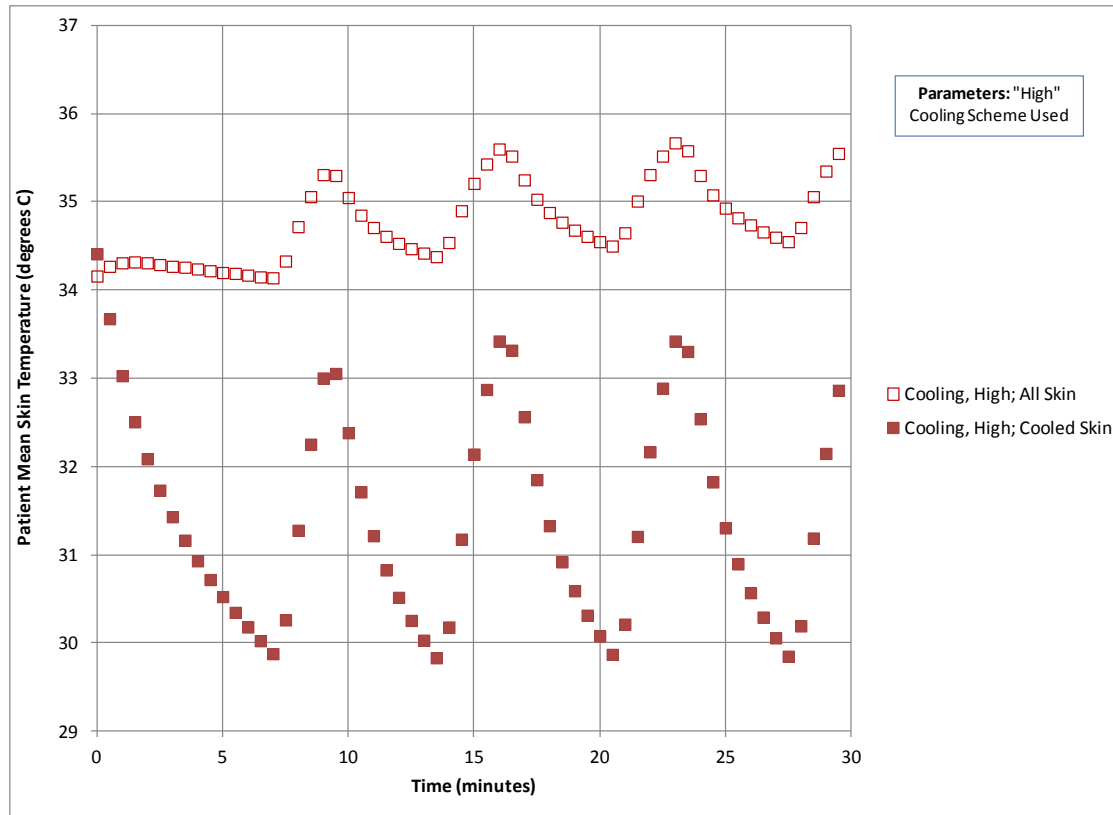
Simulation Results – Transient (2 of 5)

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Comparison of Effect of the High Cooling Method on the Mean Temperature of the Patient's Cooled Skin vs. All of the Skin:



The greater the amount of cooled skin, the closer the two values would be.

Simulation of a Novel Method for Soldier Thermal Control

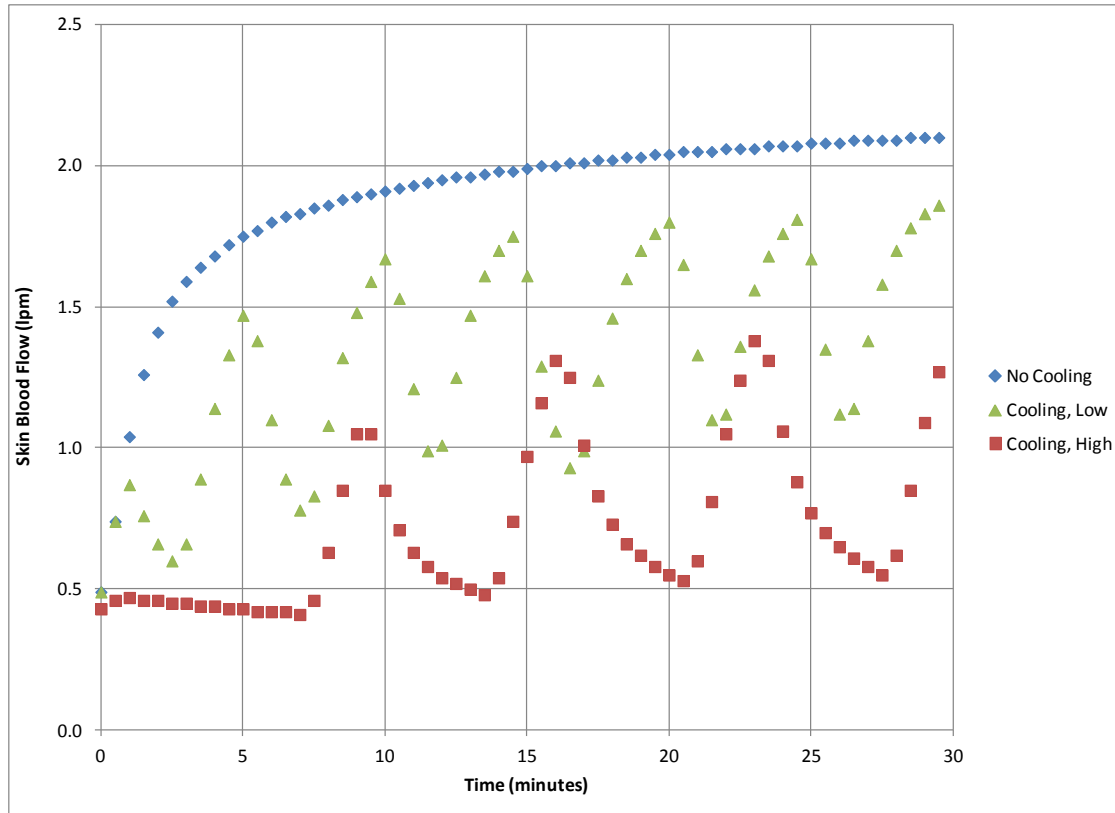
Simulation Results – Transient (3 of 5)

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Effect of Cooling Method on the Skin Blood Flow:



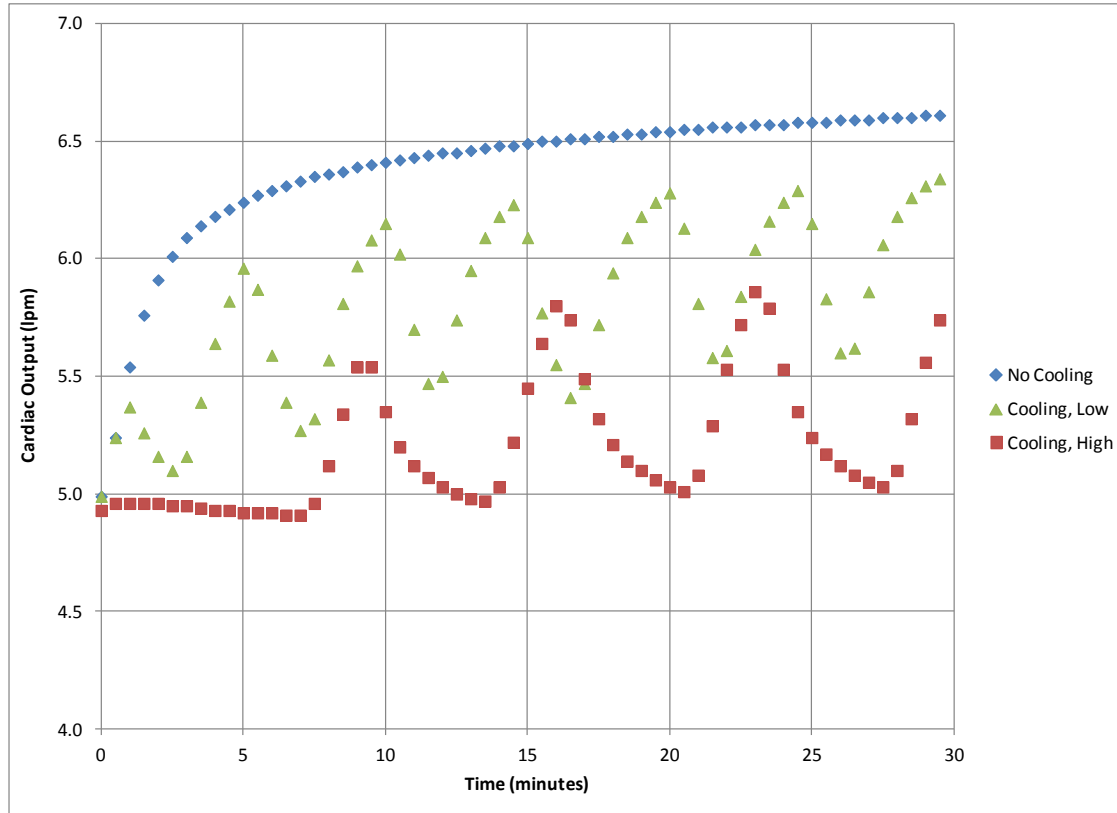
For greater amounts of applied cooling, skin blood flow decreases. For patients with peripheral injuries, lower skin blood flow – brought about by greater cooling – could be preferred for wounded warriors.

Simulation of a Novel Method for Soldier Thermal Control

Simulation Results – Transient (4 of 5)



Effect of Cooling Method on Cardiac Output:



Greater cooling results in less cardiac output, and thus cardiovascular strain.

Simulation of a Novel Method for Soldier Thermal Control

Simulation Results – Transient (5 of 5)



Required Cooling for Various Cooling Methods and for Different Soldier Initial Thermal States:

Cooling Condition	Cooling Duty Cycle (%)	
	Normothermic Initial State	Hyperthermic Initial State
None	0	0
Low	34.7	49.6
High	64.0	69.1

Although significantly more power would be required for more cooling, the benefits of reduced cardiovascular strain and skin blood flow may outweigh the required vehicle performance burdens.



Conclusions (1 of 2)

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- Cooling a greater surface area of the body – as well as proportioning the cooling to parts of the body such that a more uniform surface temperature results – would generally decrease local vasoconstriction and increase cooling efficiency.
- Higher cooling capacity for patients would present a burden, but may be outweighed by the patient benefits.
- Implementation of a skin temperature feedback control method – with “low cooling” for healthy soldiers, and “high cooling” for wounded warriors – would improve efficiency.

Conclusions (2 of 2)

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- Implementing core temperature monitoring would provide the best metric of the patient's thermal state.
- Obtaining wounded warrior physiological and thermoregulatory data, and developing appropriate predictive models with user ability to have more control over the human physiology and thermoregulation throughout the body, may be warranted.
- Interaction with Army combat casualty care personnel could yield the ideal HVAC conditions for wounded warriors.
- Future work could involve simulation of dust entrainment into the crew / patient areas, vehicle overpressure characteristics, and other health-related aspects of ground combat vehicles.