HEAT LOSS OF THE HUMAN HEAD UNDER BICYCLE HELMETS FOR DESIGNING SAFER BICYCLE HELMETS

by Guido De Bruyne
Introduction

K.U.Leuven bicycle helmet research group

- Biomechanics and Engineering Design Section
- Division of Experimental Neurosurgery and Neuroanatomy
- Mechanical Metallurgy Section
- Division M3-BIORES: Measure, Model & Manage Bioresponses
Thermoregulation

Sensible heat loss (1)
Latent heat loss (2)
Total heat production (3)

After Mount (1979)
Heat balance

\[ M + W = \{(C+R+Q_{ls}) + (C_{re}+Q_{lr})\} + S \]

through skin + respiratory

After Fanger (1970)
The head is an important area for heat loss.  
(Froese & Burton, 1957; Blair et al., 1961; Kissen, 1971; Nunneley et al., 1971)

Wearing a helmet can increase local skin temperature.  
(Coleman and Mortagy, 1973; Sheffield-Moore et al., 1997; Davis et al., 2001)

Bicycle helmets restrict the heat loss of the human head.  
(Ellis, 2003; Bruhwiler et al., 2003, 2006)

Bicycle helmet research is usually performed using thermal manikins.  
(Ellis, 2003; Bruhwiler et al., 2003, 2006)

Spatial-temporal gradients of skin and sweat production?  
Do open structures effectively improve bicycle helmet ventilation?
2. Hypothesis and Objectives

It is hypothesized that it is possible to improve the micro-climate under a bicycle helmet without compromising their impact protective function.

The **first objective** is to quantify the spatial gradients of skin temperature, air temperature and sweat production under a bicycle helmet.

The **second objective** focuses on the determination of ventilation rate through the 3D space between head and bicycle helmet.

The **third objective** is to use of mathematical models for predicting the ventilation efficiency between a virtual head and bicycle helmet.

Working towards a method for improving bicycle helmet ventilation using an active controller is the **fourth objective**.
3. Research
Spatial gradients of skin temperature, air temperature and sweat production.

The first objective was investigated using 36 experiments at 9 test persons wearing a helmet.

Test installation

Air velocity control
at 3 ms$^{-1}$

Temperature control
at 20.0°C +/- 0.5°C
Experimental design

![Graph showing work rate (W) vs. time (min) for male and female subjects. The graph indicates a difference in work rate between male and female subjects over time.]
Measurement location

Skin temperature at three locations
Air temperature at five locations
Sweat production at four locations

SKINOS SKD-4000.

Thermocouples type T and Keithley 2700
Skin temperature on the head under a helmet

$p < 0.05$
Air temperature between head and helmet

p<0.05

![Graph showing air temperature at different locations for low and high effort levels. The graph includes data points for frontal air inlet, lateral, top, rear centre, and rear lateral positions, with error bars indicating variability. Different markers and colors are used to distinguish between low and high effort levels.]
Sweat production on the head under a helmet

\[ p > 0.05 \]

![Graph showing sweat production on the head under a helmet. The graph compares sweat production at different locations (frontal, lateral, rear centre, rear lateral) for low and high effort levels. The x-axis represents different regions of the head, and the y-axis represents sweat production in mg/min/cm². Error bars are included to show variability.]
Discussion first objective

Air temperature

Sweat production
Determination of ventilation rate through bicycle helmets.

This second objective was investigated using 116 experiments at six bicycle helmets.


Experimental setup

- CO₂, ppm
- time delay (s)
- time $C^e$ (s)
- 3 m/s
- 2.1 m
- 1.5 m
- 2.3 m
Experimental setup

1) Pressurised CO$_2$ gas bottle
2) Solenoid Valve
3) Fan with CO$_2$ injection and gauze
4) Sampling of the tracer gas in the helmet
5) Multiplexer
6) Pump
7) CO$_2$ analyser
Analysis: data-based mechanistic modelling

\[ y(t) = \frac{B(s)}{A(s)} u(t - \tau) + \delta(t) \]

- \( y(t) \): measured CO2 concentration
- \( u(t) \): induced CO2 concentration
- \( \tau \): is the time delay
- \( \delta \): additive noise
- \( A(s) \) and \( B(s) \) are polynomials with model parameters

First order system:

\[ y(t) = \frac{b_0}{s + a_1} u(t - \tau) \]
Conservation law of mass:

\[
\frac{dc_i(t).vol_i.\rho}{dt} = \rho.V_{c,i}.c_0(t) - \rho.V_{c,i}.c_i(t)
\]

\[
\frac{dc_i(t)}{dt} = \frac{V_{c,i}}{vol_i}.(c_0(t) - c_i(t))
\]

\[
c_i(t) = \frac{\beta_i}{s + \beta_i} . c_0(t)
\]

**C_i**: CO₂ concentration at position i [kg contaminant . kg mixture⁻¹]

**C_0**: CO₂ concentration before the helmet [kg contaminant. kg mixture⁻¹]

**Vc,i**: local effective flow rate of the air-contaminant mixture. [m³.s⁻¹]

**β**: the local refreshment rate [m³.m⁻³.s⁻¹]
Helmets in the experiment

1. 

2. 

3. 

4. 

5.
Experimental results

Helmet 1.
Helmet 2.
Helmet 3.
Helmet 4.
Helmet 5.

The diagram shows the ventilation efficiency for each helmet, with helmet 2 having the highest efficiency compared to the others.
Helmet 1

local ventilation efficiency ($m^3 \cdot m^{-3} \cdot s^{-1}$)

Histogram

0.020 $m^3/m^3.s$

0 $m^3/m^3.s$
Helmet 2

local ventilation efficiency (m³.m⁻³.s⁻¹)
Helmet 3

local ventilation efficiency \((m^3.m^{-3}.s^{-1})\)
Helmet 4

Local ventilation efficiency ($m^3 \cdot m^{-3} \cdot s^{-1}$)

Histogram

Percentage of scalp area under Helmet 4 with corresponding ventilation efficiency.

- 0-2
- 2-4
- 4-6
- 6-8
- 8-10
- 10-12
- 12-14
- 14-16
- 16-18
- 18-20

Ventilation efficiency ($0.020 \text{ m}^3/\text{m}^3 \cdot \text{s}$)

Percentage of surface area on the head (%)

$0 \text{ m}^3/\text{m}^3 \cdot \text{s}$

$0 \text{ m}^3/\text{m}^3 \cdot \text{s}$

Histogram

$0.10^{-3} \text{ m}^3/\text{m}^3 \cdot \text{s}$

Chart showing distribution of ventilation efficiency across different scalp areas.
Helmet 5

local ventilation efficiency ($m^3.m^{-3}.s^{-1}$)

Histogram

percentage of scalp area under Helmet 5 with corresponding ventilation efficiency

<table>
<thead>
<tr>
<th>0-2</th>
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<th>4-6</th>
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ventilation efficiency ($0.020 m^3/m^3.s$)

0 $m^3/m^3.s$
No helmet

local ventilation efficiency \((m^3.m^{-3}.s^{-1})\)
Bicycle helmet parameters

1. Distance inlet to outlet, (m)
2. Projected inlet area, (m$^2$)
3. Distance head to helmet, (m)
4. Channels
5. Geometry vents
6. Position vents
Simulated versus Measured data

adjusted $r^2 = 0.92$, $p<0.05$

Parameters:
1. Distance inlet to outlet, $L$ (m)
2. Projected inlet area, $R$ (m$^2$)

\[ V = \frac{\pi R^4 \Delta P}{8\eta L} (m^3 s^{-1}) \]
Reducing bicycle helmet vents

\[ V = \frac{\pi R^4 \Delta P}{8 \eta L} \quad (m^3 s^{-1}) \]
Mathematical models for predicting ventilation efficiency

This third objective was investigated using analytical models and Computational Fluid Dynamics (CFD).

\[
\frac{\partial \tilde{v}}{\partial t} + u_j \frac{\partial \tilde{v}}{\partial x_j} = C_{b1}[1 - f_{t2}] S\tilde{v} + \frac{1}{\sigma} \{ \nabla \cdot [(\nu + \tilde{v})\nabla \tilde{v}] + C_{b2} |\nabla \nu|^2 \} - \left[ C_{w1} f_w - \frac{C_{b1}}{\kappa^2} f_{t2} \right] \left( \frac{\dot{\nu}}{d} \right)^2 + f_{t1} \Delta U^2
\]

Rate of change of viscosity parameter \( \tilde{v} \) + Transport of \( \tilde{v} \) by convection = Transport of \( \tilde{v} \) by turbulent diffusion + Rate of production of \( \tilde{v} \) - Rate of dissipation of \( \tilde{v} \)

Simulated setup

Standard configuration

Modified configuration

33
Local mean age of air

Ventilation efficiency was calculated as local mean age of air, $\tau_i$ (s)

$$\tau_i = \int_0^\infty \left(1 - \frac{c_i(t)}{c_i(\infty)}\right) dt$$

$$\beta = \frac{1}{\tau_i}$$

t = time (s)

$c_i$ = tracer gas concentration at point $i$ (kg/kg)

$\beta$ = air refreshment rate or ventilation efficiency
CFD data versus measured data

quantitative data

Experimental results: 1-20 \(10^{-3}\cdot m^3 \cdot m^{-3} \cdot s^{-1}\)
Simulated results: 32-42 \(10^{-3}\cdot m^3 \cdot m^{-3} \cdot s^{-1}\)

normalised results (0 - 1)

(projected top view of head under helmet)
Qualitative analysis

direction airflow

airflow direction

smoke experiments
A new bicycle helmet concept

1. Improving projected inlet area.
2. Reduce distance inlet to outlet.
3. Air channels.
4. Reduce vent area
Results of the new bicycle helmet

Relative improvement in ventilation efficiency per location (%)

Location on the scalp under the bicycle helmet (1-13).
Towards an active ventilated bicycle helmet

Transient behaviour of sweat production was monitored at six persons wearing a helmet and nine persons wearing a helmet.


Experimental design

Six test persons wearing no helmet.

![Graph showing work rate (W) over time (min) for male and female participants. Each participant performs work at different rates: male at 150 W, female at 125 W, male at 80 W, and female at 50 W. The graph plots time in minutes on the x-axis and work rate in watts on the y-axis.]
Experimental design

Climatic conditions:

1. Air velocity 2.4 m/s (standard condition) and 0.0 m/s (warm condition)
2. Ambient temperature: 16.0°C +/- 0.2°C (standard condition)
   and 27.0°C +/- 0.5°C (warm condition)
Analysis

\[ y(t) = \frac{B(s)}{A(s)} u(t - \tau) + \delta(t) \]

- \( y(t) \): measured sweat production
- \( u(t) \): the work rate
- \( \tau \): is the time delay
- \( \delta \): additive noise

\( A(s) \) and \( B(s) \) are polynomials with model parameters
Time delay in sweat production

\[ p > 0.05 \]

\[ \text{Dynamics of sweat production} \]

\[ [27.0^\circ \text{C} \& 0.0 \text{ m/s}] \]

\[ [16.0^\circ \text{C} \& 2.4 \text{ m/s}] \]
Time delay in sweat production

$p < 0.05$
Steady state gain of sweat production

$p > 0.05$

![Graph showing steady state gain of sweat production under warm and standard conditions. The graph includes data points for left temple, right temple, and frontal region under both warm (27.0°C & 0.0 m/s) and standard (16.0°C & 2.4 m/s) conditions.]
dynamics of sweat production

constant steady state
sweat production [mg/(min.cm^2)]

Time (s)

warm condition
(0.1 m/s, 28.3°C)

standard condition
(2.4 m/s, 16.1 °C)

50-80W
Low Work Rate

125-150W
High Work Rate
Experimental design

Nine test persons wearing a helmet.

Experiments performed at 20°C.

Experimental data:
De Bruyne et al. (2008)
Analysis

Sweat Production

Absolute Humidity

Work Rate

Transfer Function

Absolute air humidity

Work rate

Sweat production

Time (min)

\[
(\text{mg.min}^{-1}.\text{cm}^{-2}) \\
(\text{g}_{\text{water}}.\text{kg}_{\text{dry air}}^{-1})
\]
Results

Time constant
p = 0.44

Steady State Gain
r = 0.72, p<0.05
discussion

1. Towards active controlled bicycle helmets.
2. Physiological insight.
3. Making thermal manikins more accurate.
4. Thermal comfort?
General conclusions

1. Higher **air temperature** (3°C) and **sweat production** (30%-50%) in the volume between head and helmet towards the rear.

2. Only **17%-18%** of the **fresh air** in front of a bicycle helmet **enters** it. Moreover, fresh air concentration can diminish with 95% from the front of the head under a helmet to the rear.

3. CFD simulations confirmed the low ventilation efficiency of bicycle helmets.

4. Smoke visualisations showed that most of the **air flows over** the currently available bicycle helmet.

5. A **new prototypes bicycle helmet** showed that it is possible to design bicycle helmets with 3 times less vent area, that are on average 16% ventilated more.

6. If **active ventilation** is considered, than controllers could be designed that respond to the (dynamic) changes of sweat production.

7. **Sweat production** under bicycle helmets can be **monitored** using cheap and widely available temperature and humidity sensors.
Future (Academic) Research

1. Thermal comfort guidelines for bicycle helmets
2. Sweat production measurements techniques