Real-time Assessment of Thermal-Work Strain: Algorithmic Basis and Validity

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Outline

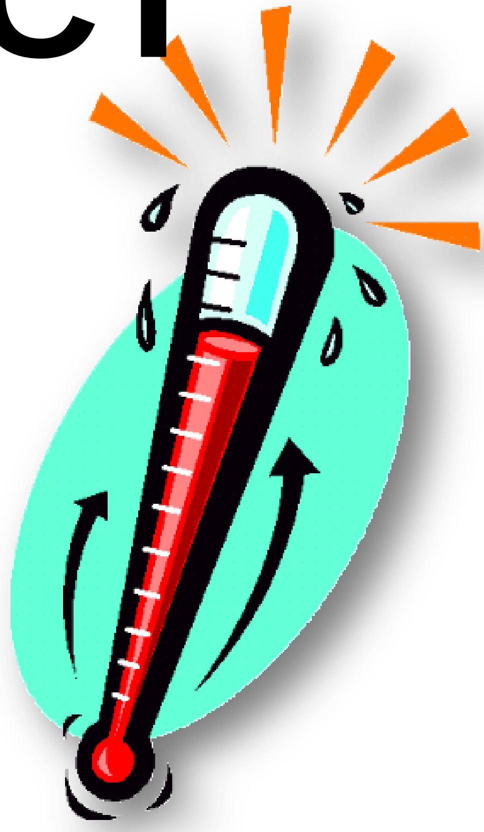
- Thermal-Work Strain Monitoring Need
- Solution: The Physiological Strain Index (PSI)
- Problem of measuring Core Temp.
- Estimated Core Temperature (ECTemp) Model
  - Physiological Basis of Model
  - Development
  - Validation
- Real-time use of ECTemp in PSI

Thermal-Work Strain State?

Engine Strain

Thermal Work Strain

HR + CT



Thermal-Work Strain State

- Physiological Strain Index (PSI)

$$PSI = 5\left(\frac{CT_t - CT_{rest}}{39.5 - CT_{rest}}\right) + 5\left(\frac{HR_t - HR_{rest}}{180 - HR_{rest}}\right)$$

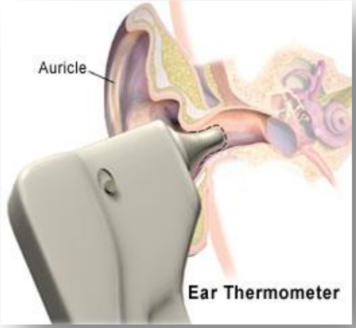
- Simple 0 to 10 index
- PSI = 10
  - HR =180 beats/min.
  - CT = 39.5 °C (103.1 °F)
  - Thermal injury is likely

PSI	Thermal-Work Strain
<5	Low
5-6	Moderate
7-8	High
9-10	Very High
>10	Extreme

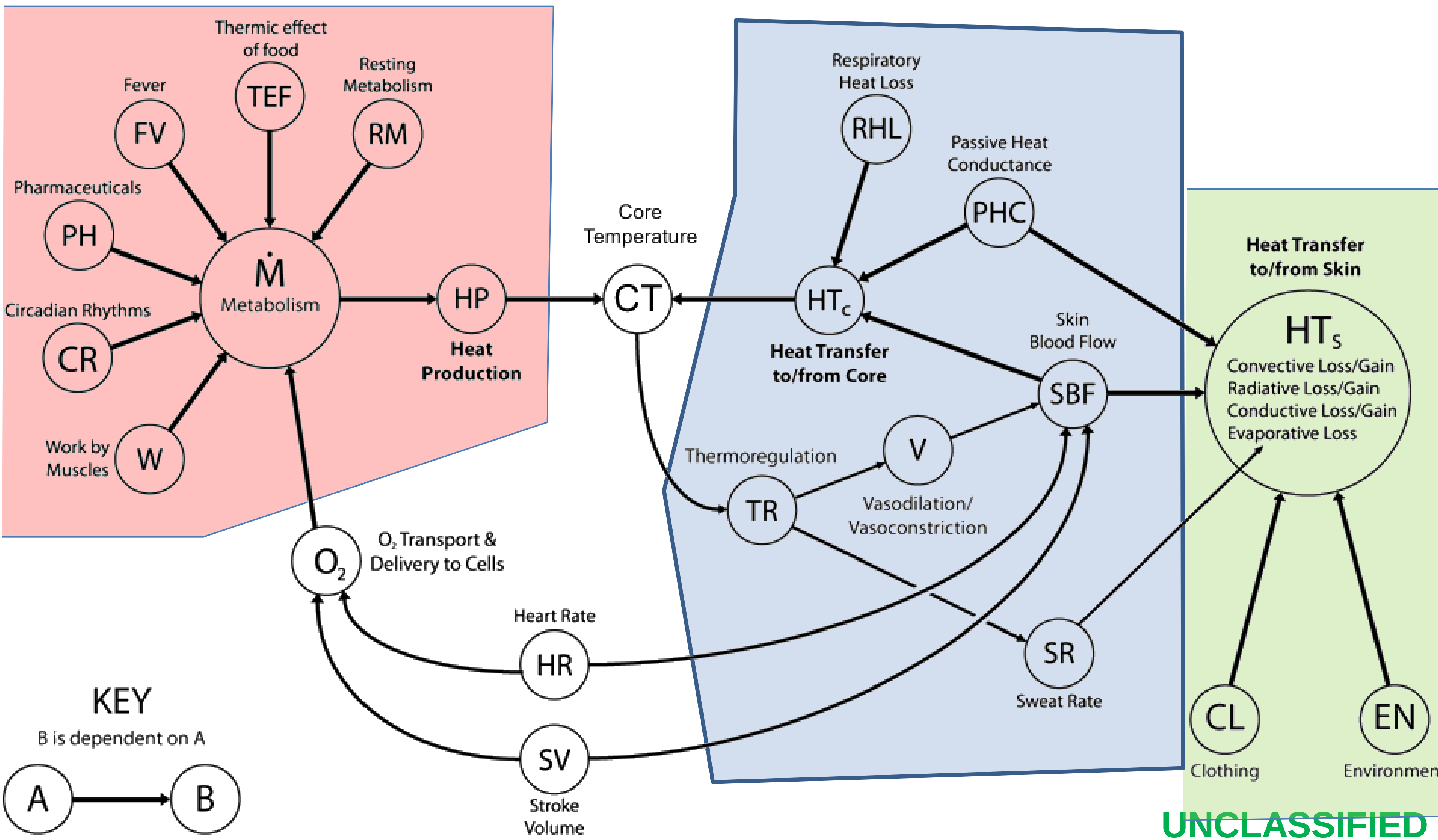
*Moran DS, Shitzer A, and Pandolf KB 1998, Moran DS 2000

Problem of CT Measurement

- Rectal /Esophageal
  - Lab gold standards
  - Not practical in field
- Core temperature pill
  - Works in controlled studies
  - Costly, contra-indicated for some,
  - Prone to error with ingested fluids
- Skin and Tympanic Temperatures
  - Error from environment, error from placement, individual differences



Estimated Core Temp. Model



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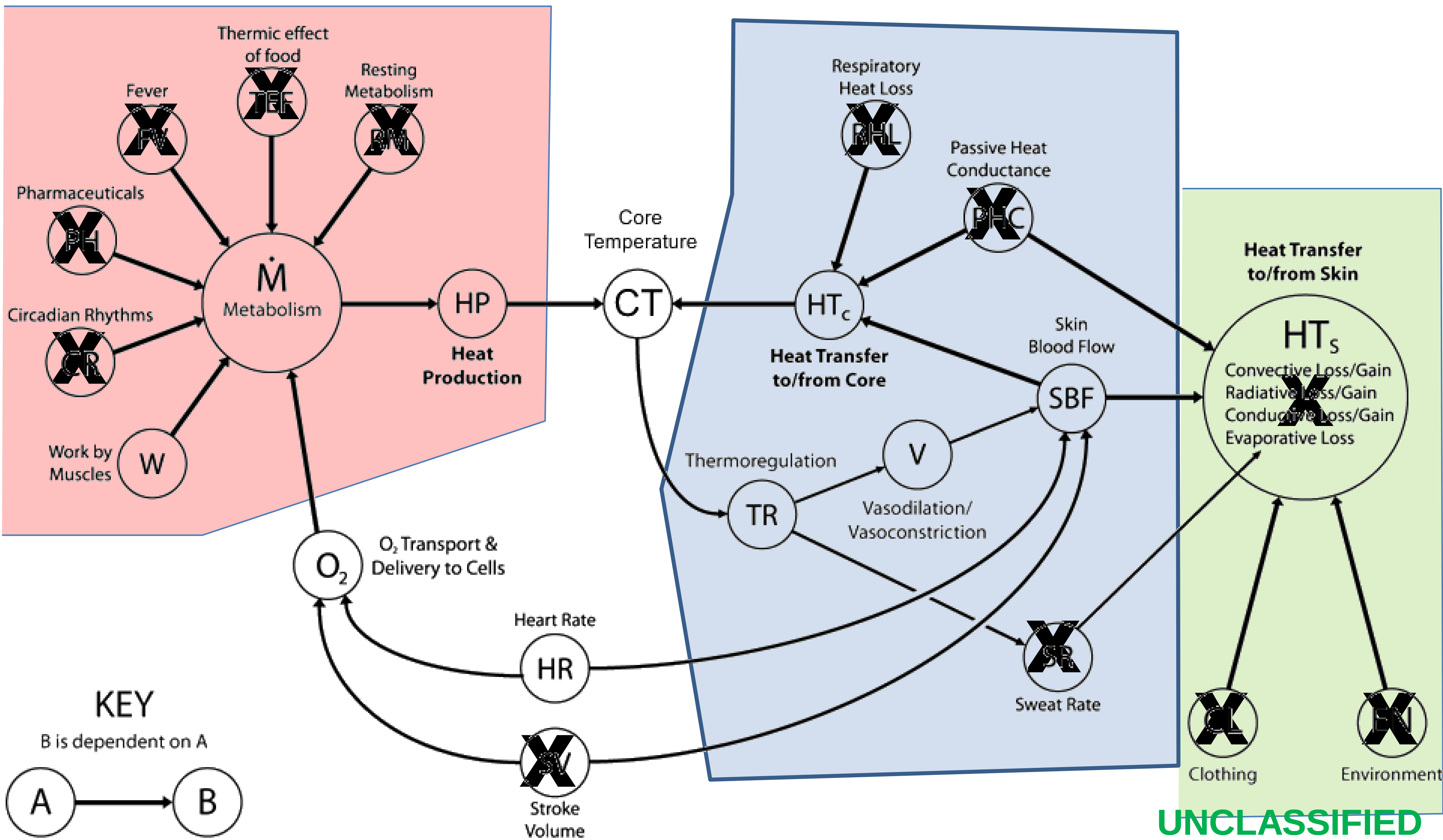

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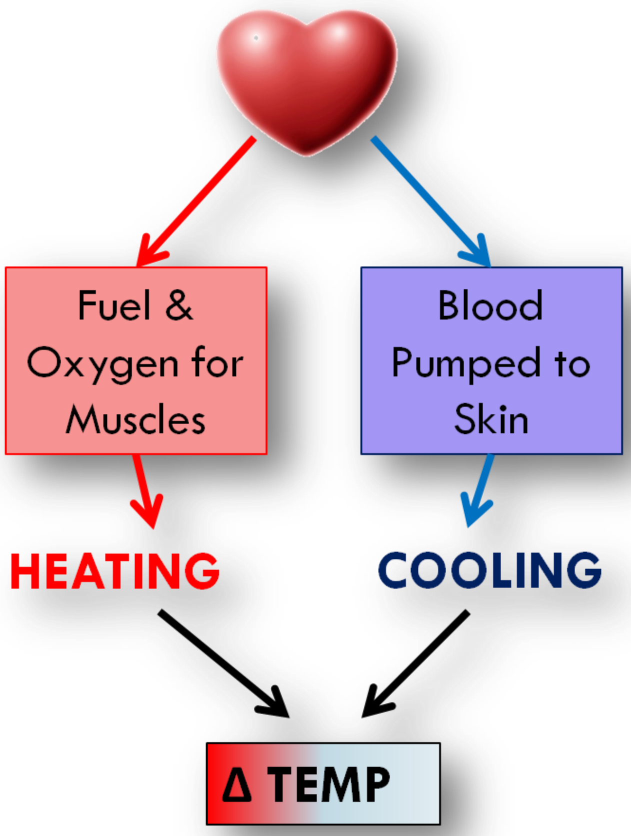
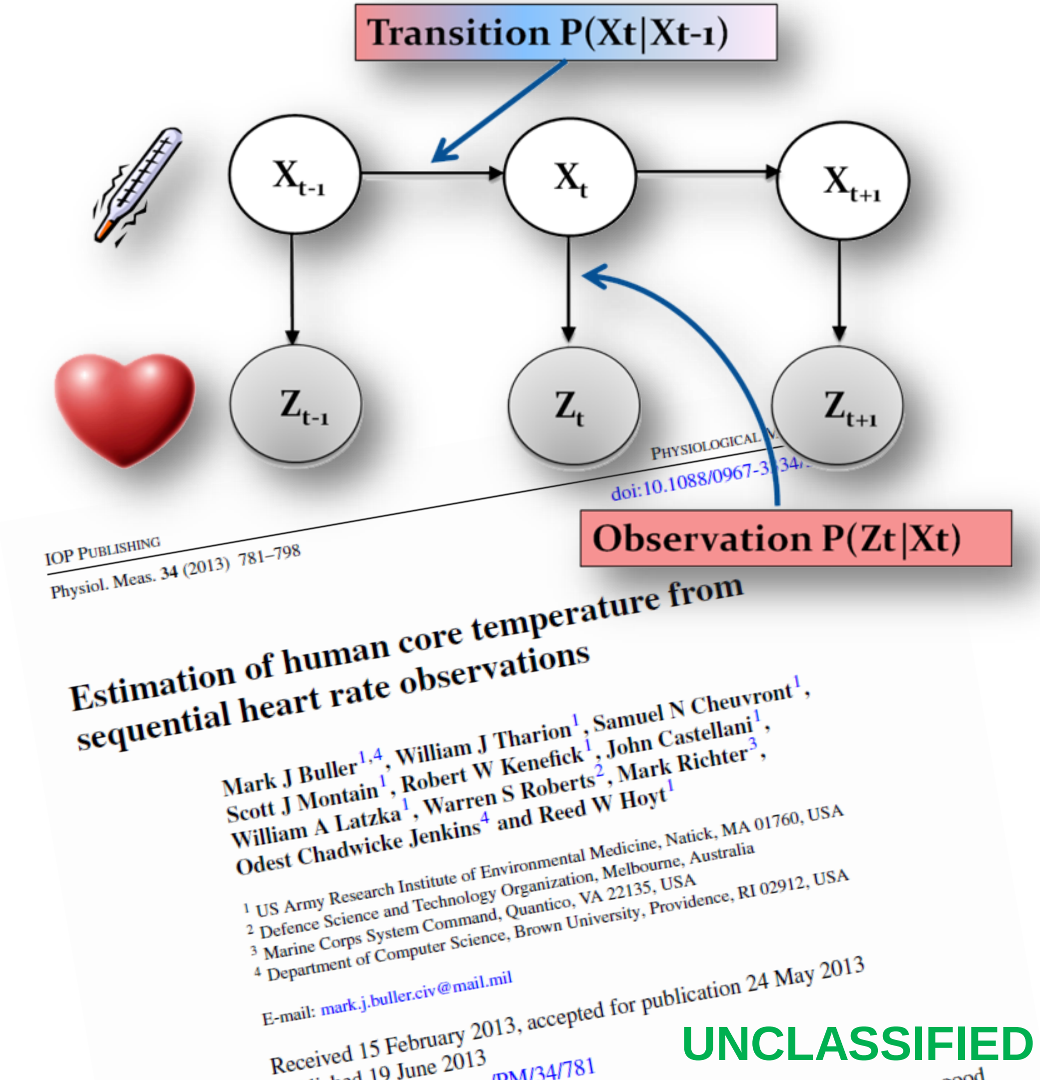
Estimated Core Temp. Model

HR "Noisy" Observation of Core Temp





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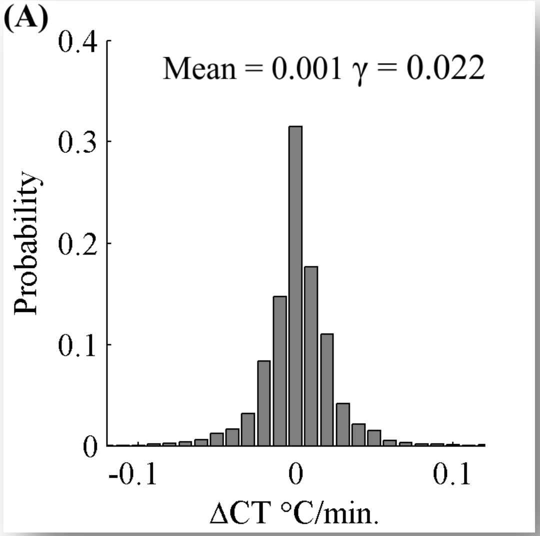
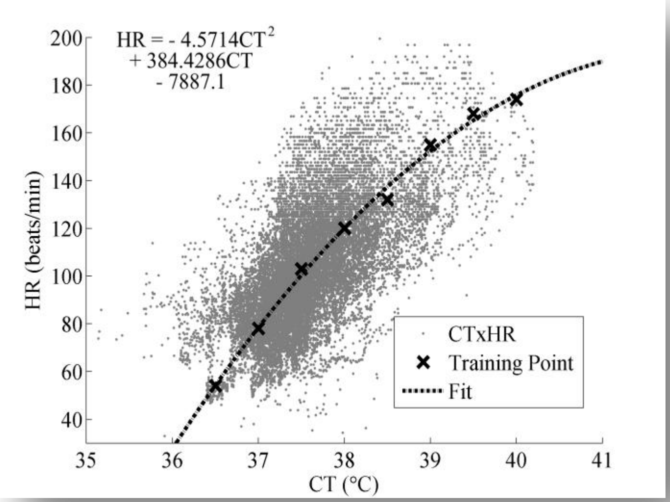
Learned Models

1. To use a Kalman Filter you need two models:
   i. How does core body temperature change from time step to time step?

   ii. How does steady state core temperature relate to steady state heart rate?





Algorithm Validation

- 9 Studies, 87 Subjects, >50,000 data points
- Different: Exercise Intensity, Environmental Conditions, Clothing (shorts and t-shirt – full encapsulation), Hydration, and Acclimation.

Study	Time (min.)	n	Age (yrs)	Height (m)	Wt. (kg)	Body Fat (%)	TEE Rate (W)†	Air Temp. (°C)	RH (%)
A	~480 x 6	18*	22±4	1.77±0.04	81±15	N/C	350/470	20–40	30–50
B	121/121	8	23±3	N/C	72±12	N/C	1000	33	50
C	111/28	6/8	23±6	1.76±0.06	76±15	18±6	675	35	55
D	59/100	7	24±7	1.78±0.08	80±21	16±11	550	45	20
E	140	11	27±6	1.77±0.05	82±5	14±3	675	25	85
F	1441	7	27±2	1.78±0.08	86±6	N/C	200	9–13	83–95
G	209+250	8	21±1	1.80±0.07	85±9	15±3	200	39–47	9–13
H	683+488	8	21±2	1.84±0.04	86±6	16±3	400	20	20–26
I	297/244	8	28±6	1.95±0.09	86±14	13±4	Var./685	15–20	65–85

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D	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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F	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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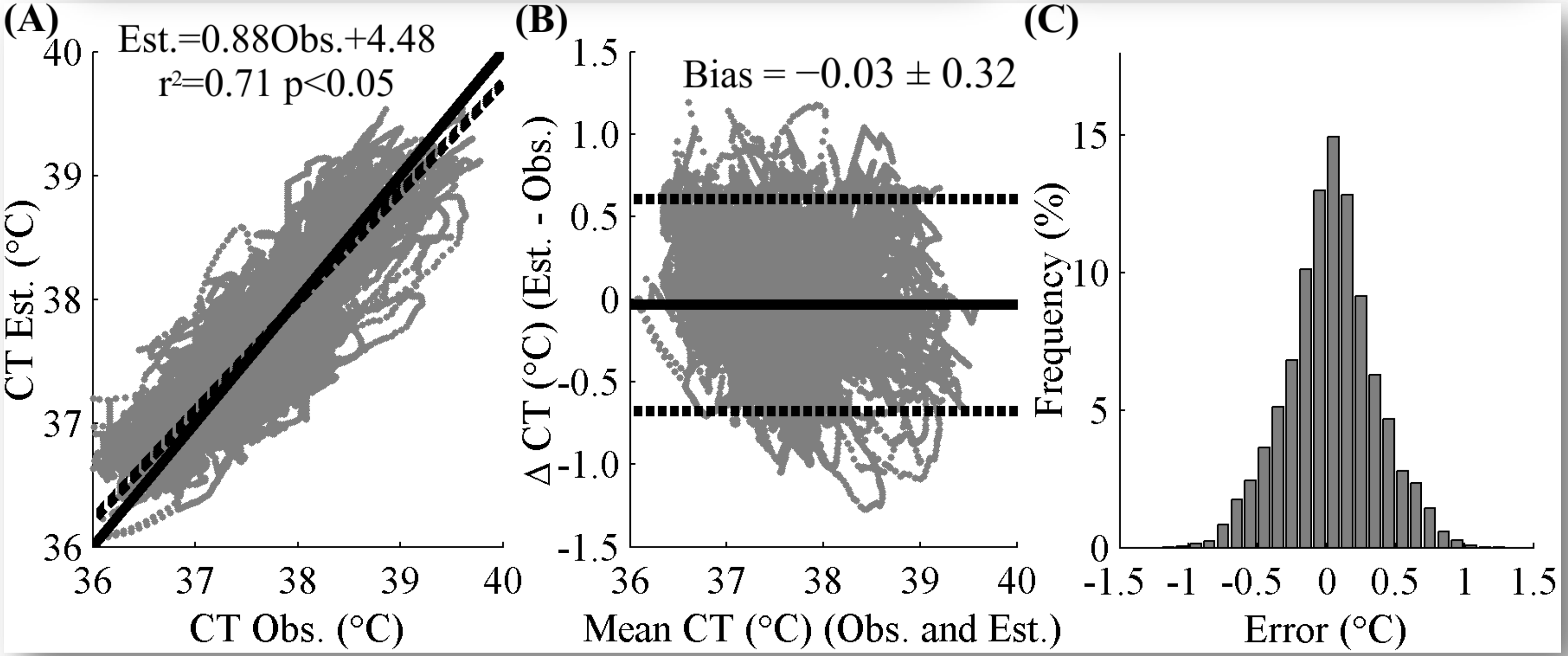
The algorithm has been validated across a large population including:

U.S. Marines in Iraq and Afghanistan
U.S. Army Ranger Students
U.S Special Forces

Results

Estimation Algorithm
Bias = – 0.03°C
95% of estimates fall within ± 0.63°C

Gold Standard
Bias = 0.06°C
95% within ± 0.58°C



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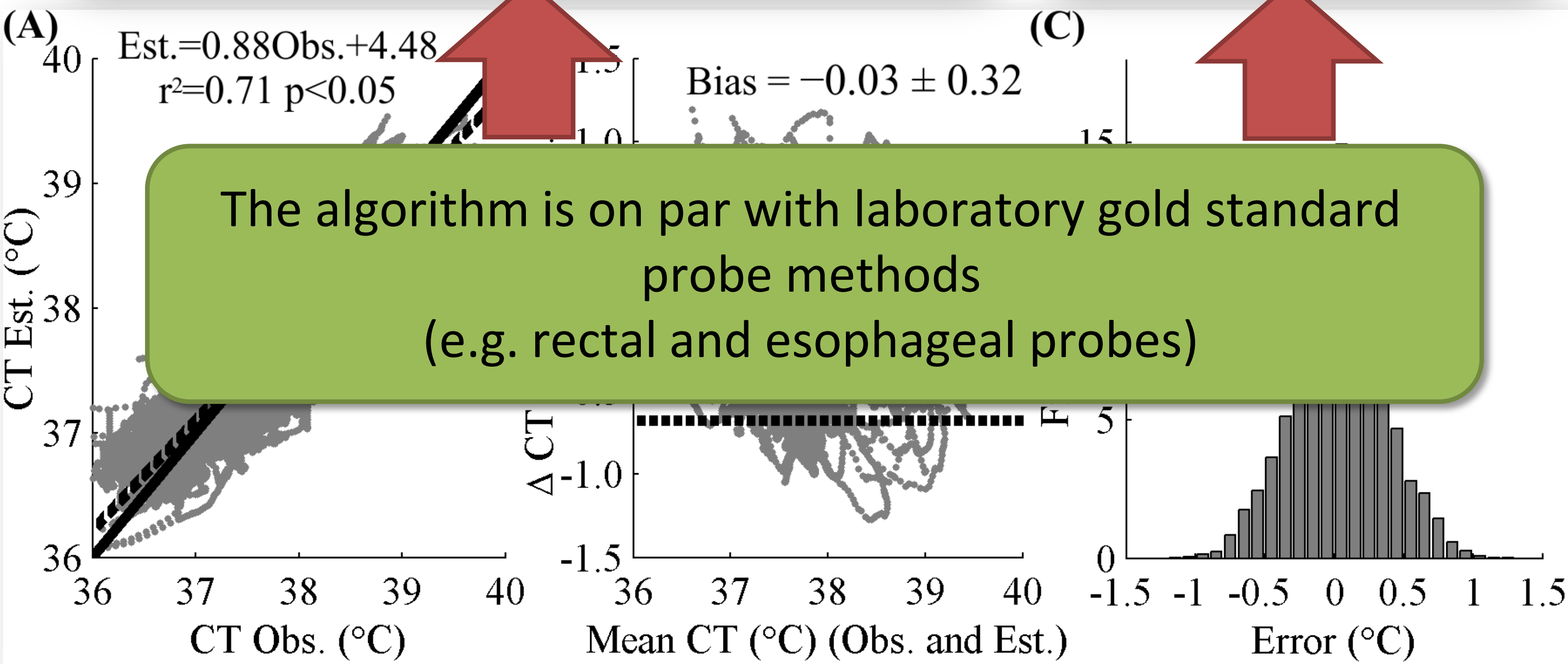


The algorithm is on par with laboratory gold standard probe methods
(e.g. rectal and esophageal probes)

CBRNE Validation

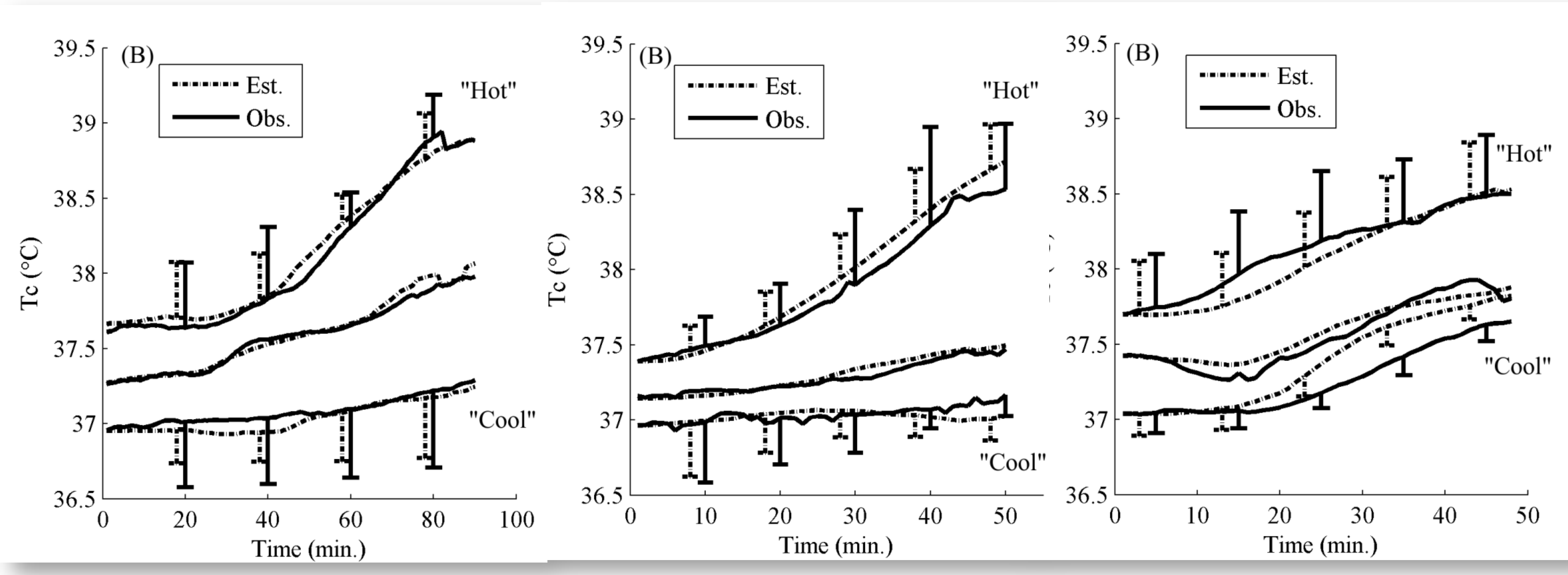
- 22^{nd} Chemical Battalion, 1^{st} WMD-CST, 95^{th} WMD-CST
- 3 Different CBRNE Training Events
  - 45 to 90 minute events over 2 to 3 days

Analysis

- Performance
  - Root Mean Square Error (RMSE)
  - Bias and Limits of Agreement (LoA)
- Questions
  - Does the model perform the same between:
    - Training events
    - Volunteers who got the hottest versus those who remained cool
    - Different time points

Event and Hot/Cool Differences?

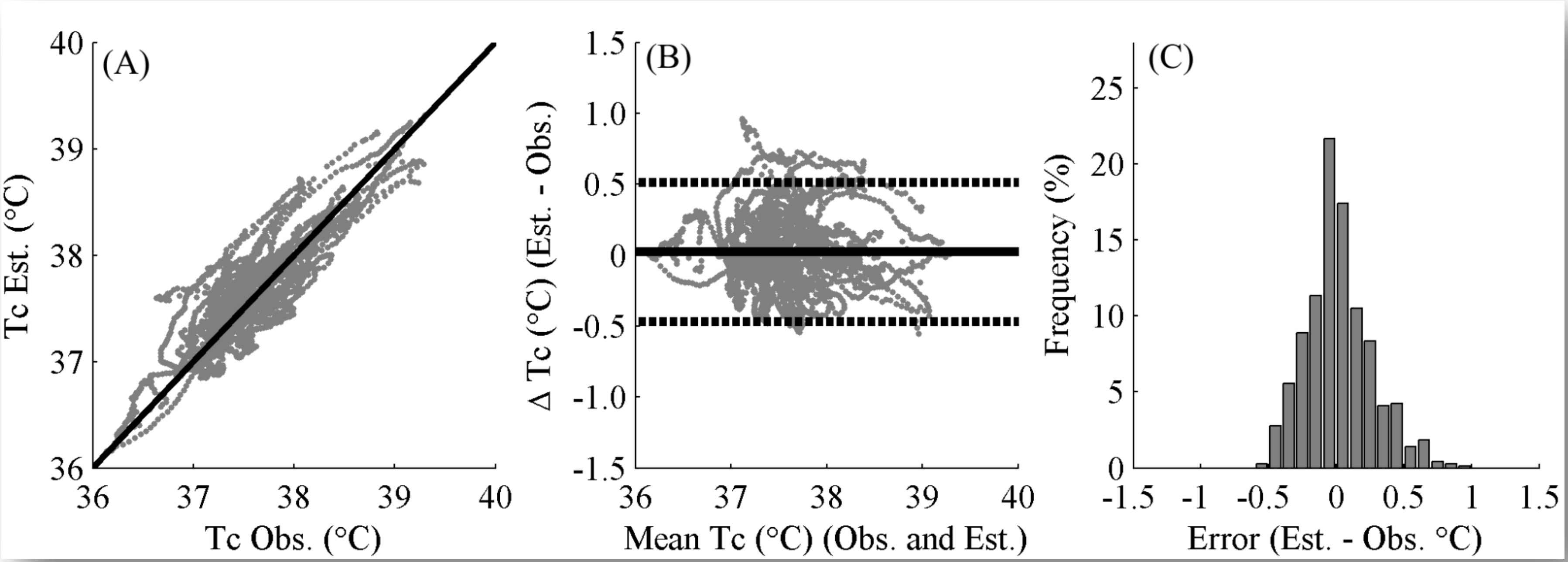
Hot = Quartile of “hottest” (highest core temperatures)
Cool = Quartile of “coolest” (lowest core temperatures)



- No significant differences between:
  - Event
  - Hottest quartile and Coolest quartile

Overall Results

Bias = 0.02°C, LoA = ± 0.48°C



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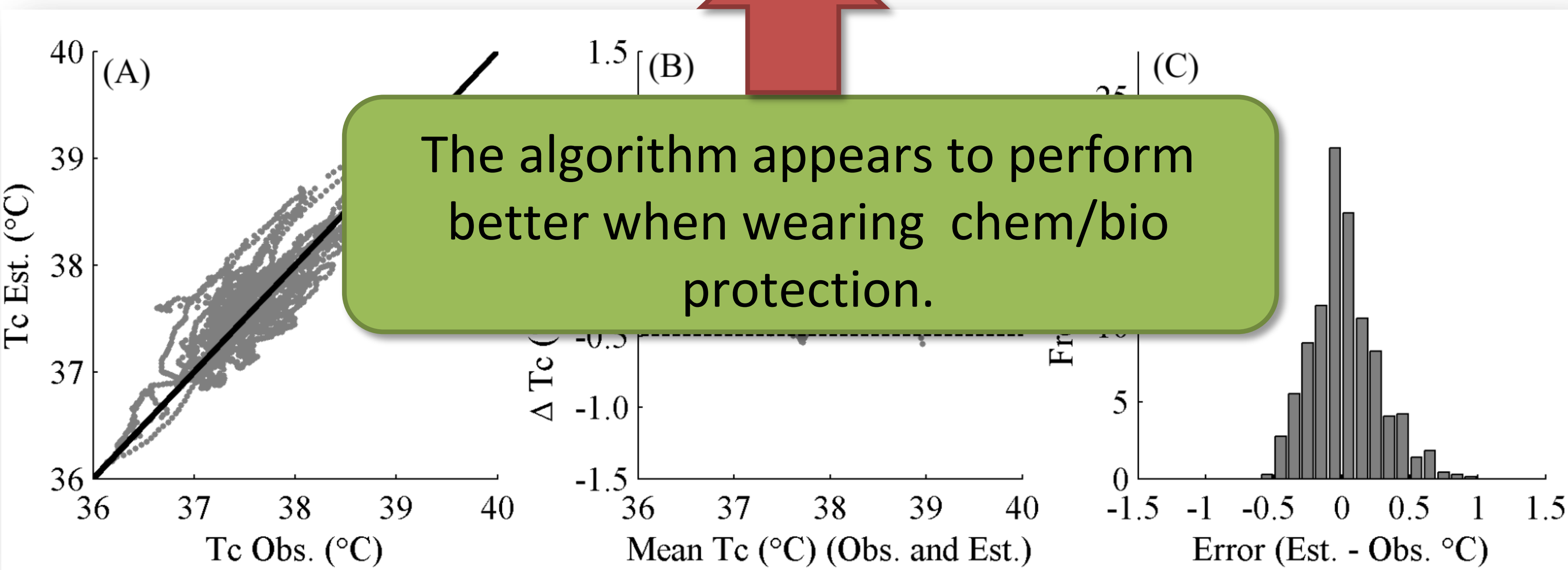
The algorithm appears to perform better when wearing chem/bio protection.



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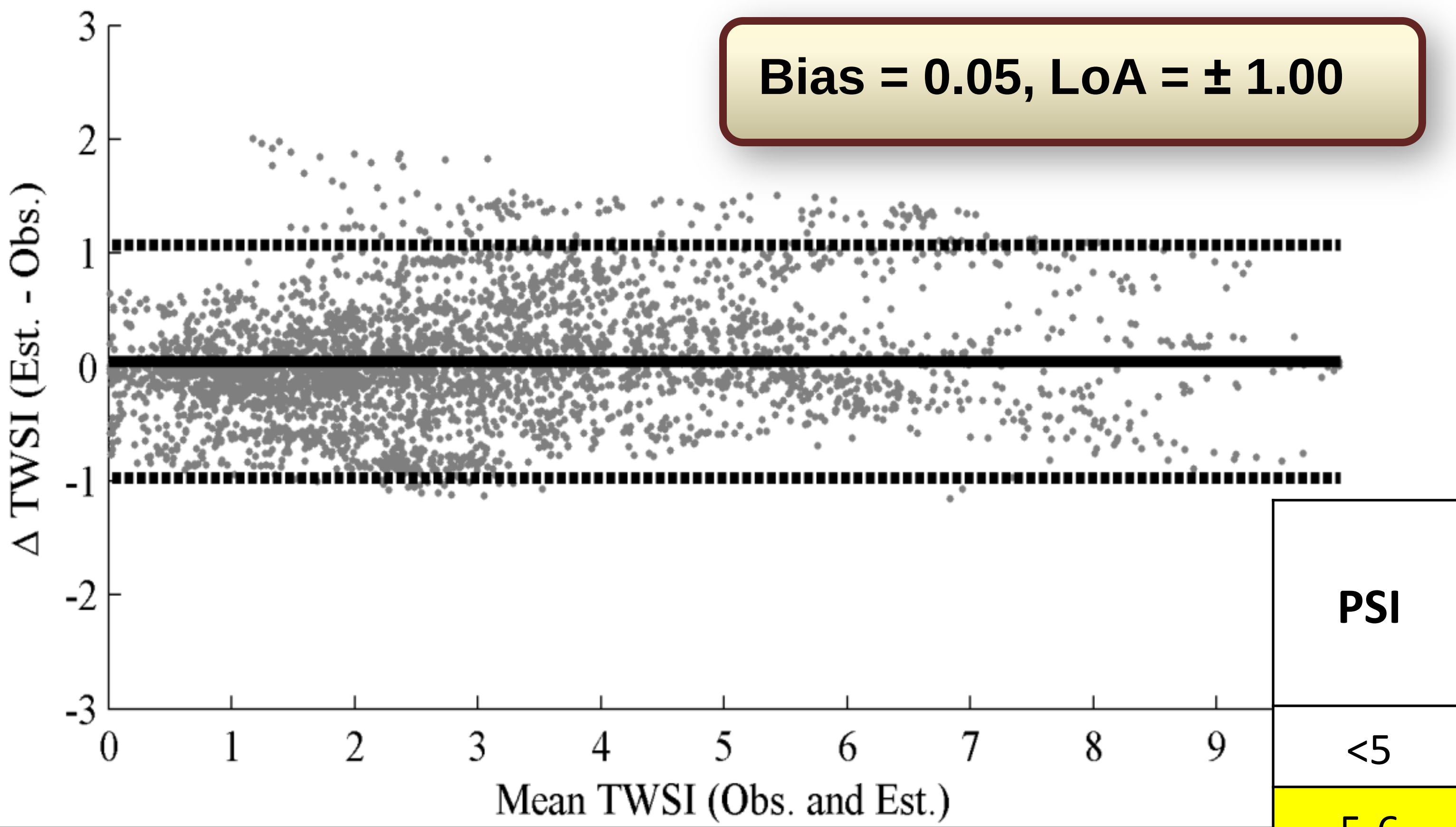
Practical Application



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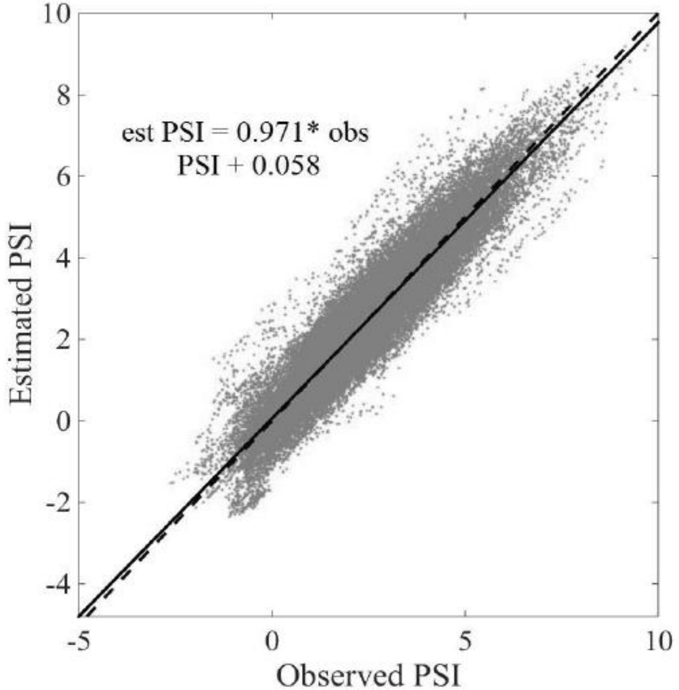
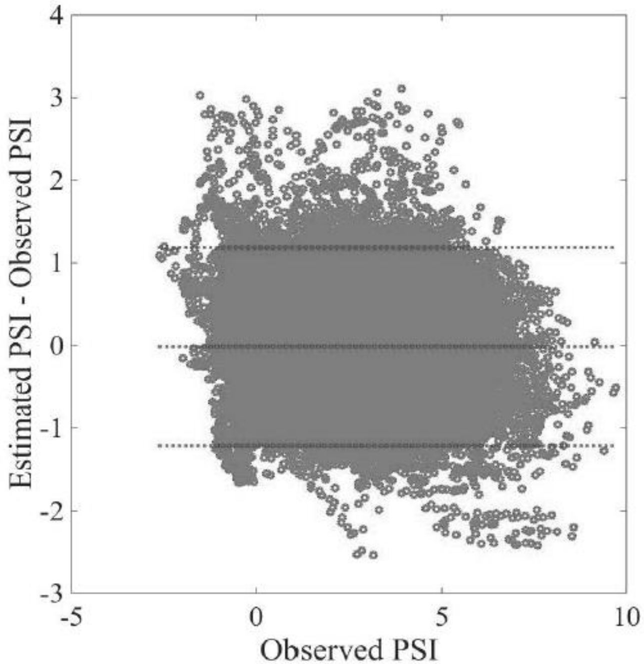
IV&V

- MIT Lincoln Laboratory, Data from USMC Marine Expeditionary Rifle Squad
- 30 U.S. Marines, Jungle Warfare Training Center, Okinawa Japan, 12 Days, ~ 8 hours per day.
- Small bias and limits of agreement - 0.01 ± 1.20





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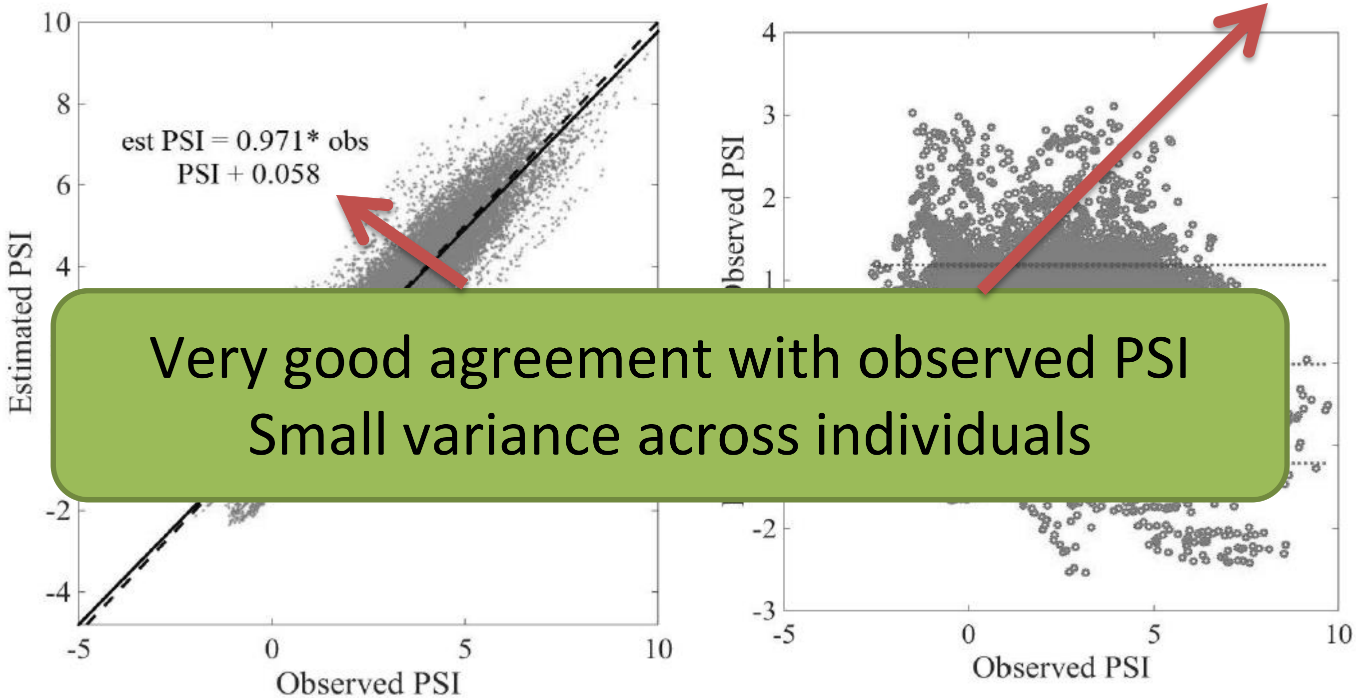

Very good agreement with observed PSI
Small variance across individuals

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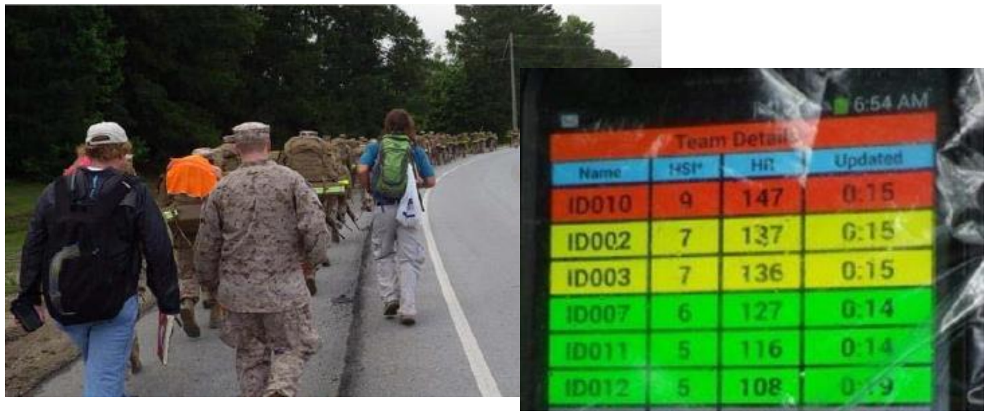
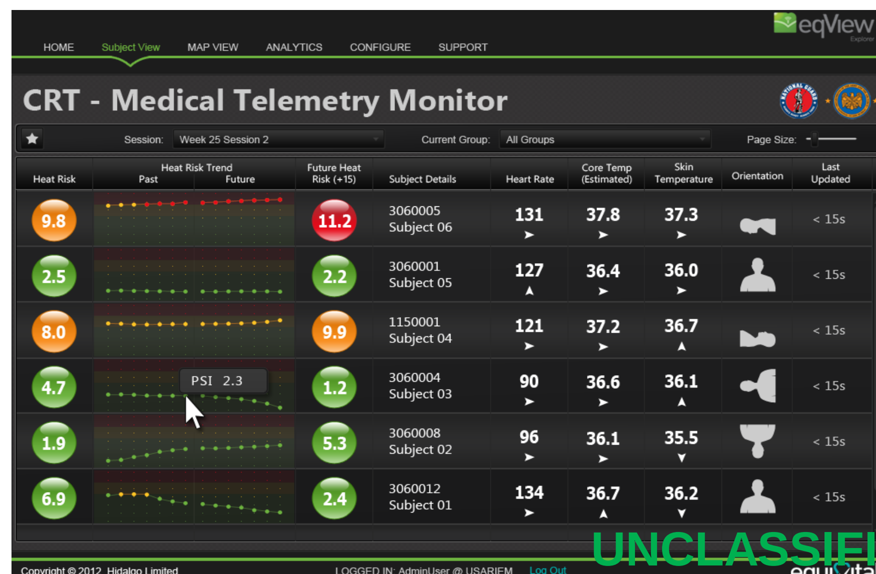
Real-Time Use

- US Marine Corps, Camp Geiger, School of Infantry – East (2015)



- 22nd Chemical Battalion, 1st WMD-CST, 95th WMD-CST, (2012 and 2013)



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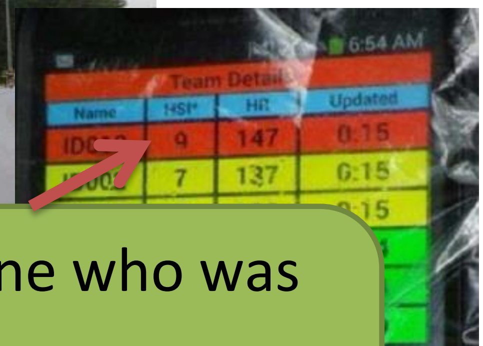
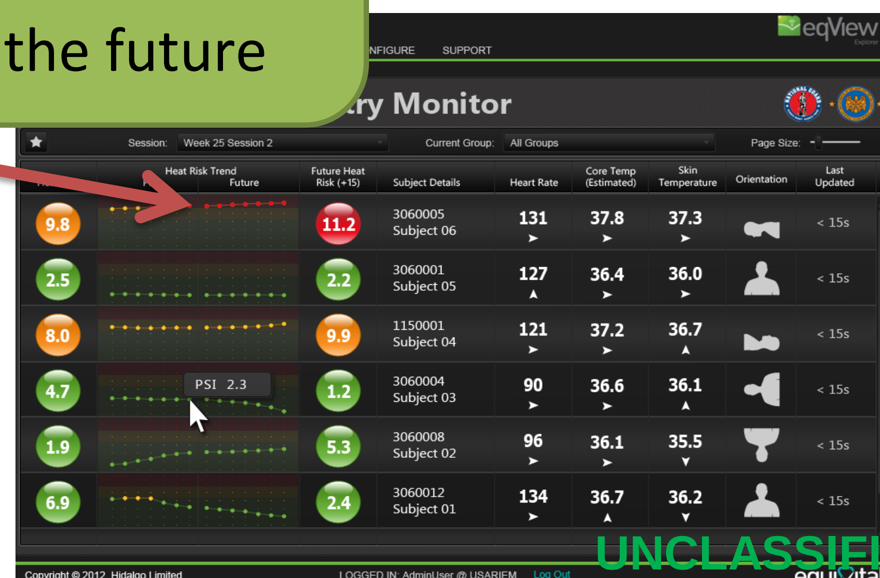


High PSI used to identify Marine who was struggling

PSI predicted 15 minutes into the future

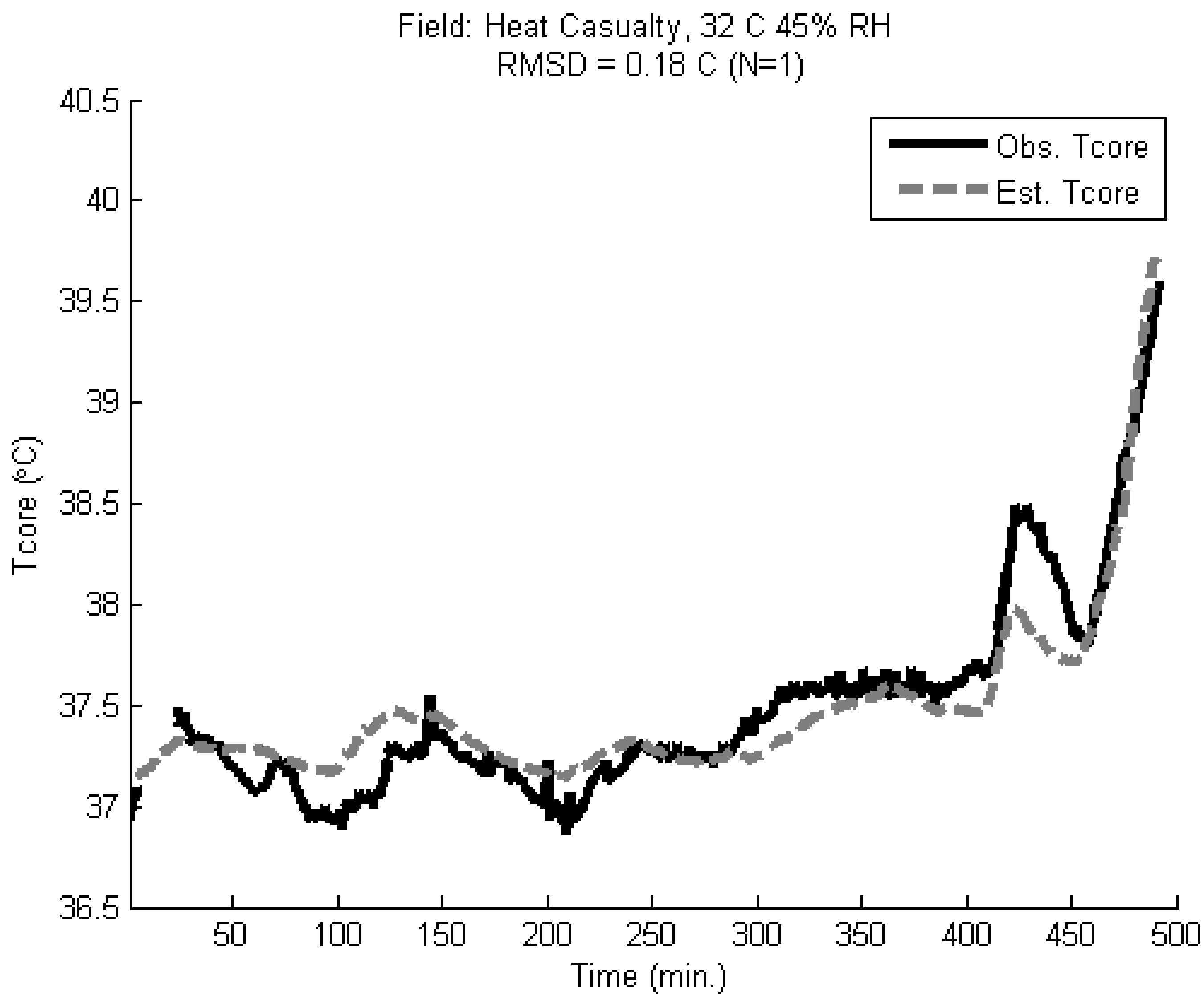
- …ST, (2012 and 2013)



Conclusions

- Core temperature prediction algorithm:
  - based on classic physiology and established signal processing methods
  - performance similar to laboratory gold standard
- Validated and independently verified
- Using estimated core temperature within PSI has been demonstrated in real-time during field training

Example Heat Casualty



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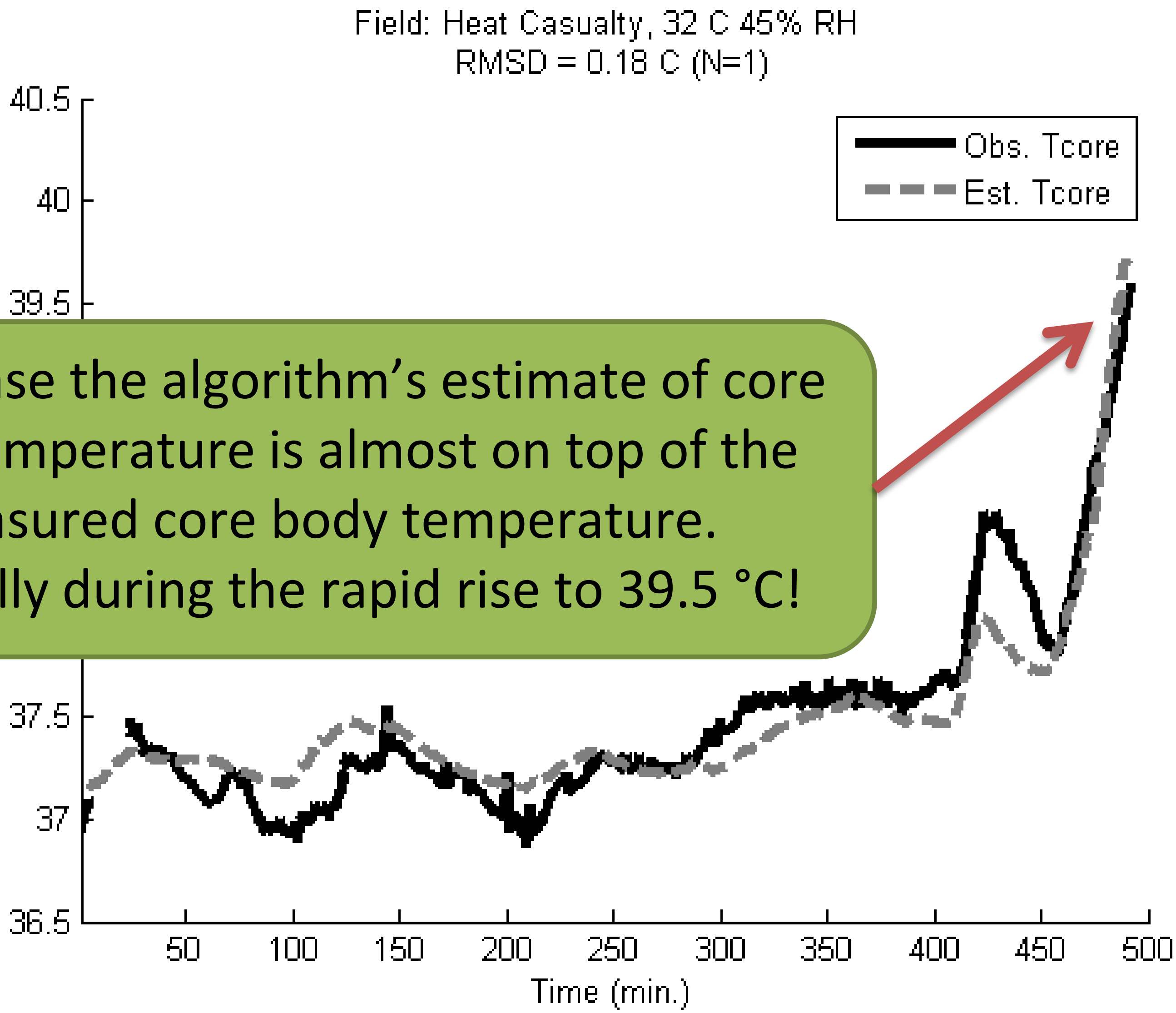

In this case the algorithm's estimate of core body temperature is almost on top of the measured core body temperature. Especially during the rapid rise to 39.5 °C!

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