STATSCALE INDUSTRY WORKSHOP 2023
20TH APRIL 2023 AT THE WELLCOME COLLECTION LONDON UK

CREW HEALTH AND PERFORMANCE DATA ANALYSIS USING CHANGE DETECTION TECHNIQUES*

Invited Speaker: **Kyoung Jae Kim**, Ph.D., *KBR, Houston, TX, USA*
Jeffrey Somers, M.S., Renita S. Fincke, *NASA JSC, Houston, TX, USA*

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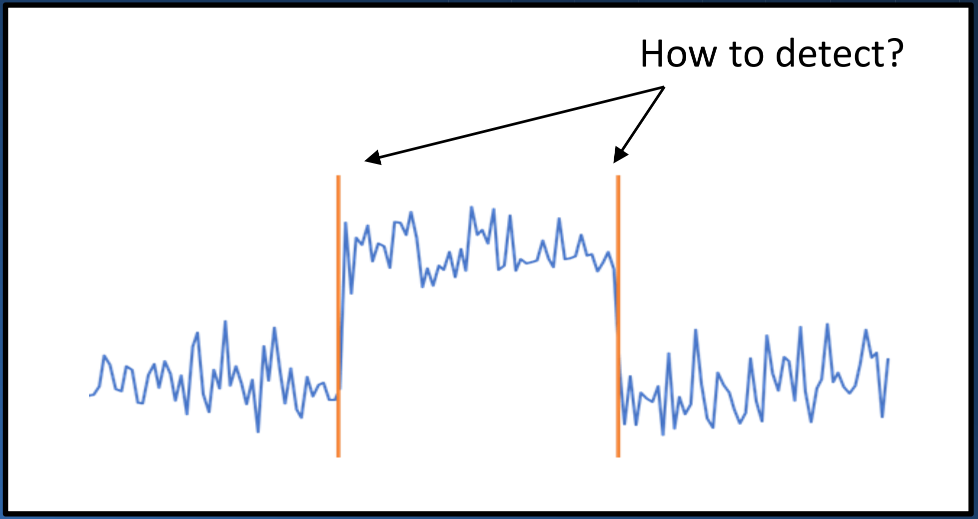
Motivation

- *Why "Change Point Detection" Is Needed*
  - Event detection is needed while analyzing physiological waveforms or derived measurements
  - Event detection methods have traditionally been based on a subjective visual analysis, but this is time-consuming, and requires 2–3 trained personnel with an independent reviewer
  - Typical computerized methods (e.g., digital filtering, linear regression, peak detection) occasionally provide unwanted detection results from data with randomly distributed or sparse noises. ➔ Wrong event detection goes to inaccurate data analysis
  - Need to detect change points accurately and automatically to support crew health and performance data analysis



Our Two Publications

frontiers in Physiology

ORIGINAL RESEARCH
published: 17 December 2021
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Novel Computerized Method for Automated Determination of Ventilatory Threshold and Respiratory Compensation Point

Kyoung Jae Kim[1], Eric Rivas[1], Brian Prejean[1], Dillon Frisco[2], Millennia Young[3] and Meghan Downs[3]*

[1]KBR, Houston, TX, United States, [2]JES Technologies, Houston, TX, United States, [3]NASA Johnson Space Center, Houston, TX, United States

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Edited by:
Gary W. Mack, Brigham Young University, United States

Reviewed by:
Stephen Seiler, University of Agder, Norway
Glen E. Foster, University of British Columbia Okanagan, Canada

Correspondence:
Kyoung Jae Kim
kyoungjae.kim@nasa.gov

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Introduction: The ventilatory threshold (named as VT_1) and the respiratory compensation point (named as VT_2) describe prominent changes of metabolic demand and exercise intensity domains during an incremental exercise test.

Methods: A novel computerized method based on the optimization method was developed for automatically determining VT_1 and VT_2 from expired air during a progressive maximal exercise test. A total of 109 peak cycle tests were performed by members of the US astronaut corps (74 males and 35 females). We compared the automatically determined VT_1 and VT_2 values against the visual subjective and independent analyses of three trained evaluators. We also characterized VT_1 and VT_2 and the respective absolute and relative work rates and distinguished differences between sexes.

Results: The automated compared to the visual subjective values were analyzed for differences with *t* test, for agreement with Bland–Altman plots, and for equivalence with a two one-sided test approach. The results showed that the automated and visual subjective methods were statistically equivalent, and the proposed approach reliably determined VT_1 and VT_2 values. Females had lower absolute O_2 uptake, work rate, and ventilation, and relative O_2 uptake at VT_1 and VT_2 compared to men ($p \leq 0.04$). VT_1 and VT_2 occurred at a greater relative percentage of their peak VO_2 for females (67 and 88%) compared to males (55 and 74%; main effect for sex: $p < 0.001$). Overall, VT_1 occurred at 58% of peak VO_2 and VT_2 occurred at 79% of peak VO_2 ($p < 0.0001$).

Conclusion: Improvements in determining of VT_1 and VT_2 by automated analysis are time efficient, valid, and comparable to subjective visual analysis and may provide valuable information in research and clinical practice as well as identifying exercise intensity domains of crewmembers in space.

Keywords: incremental exercise, noninvasive measurement, ventilatory threshold, respiratory compensation point, automated determination

Link

The Partial Pressure of Inspired Carbon Dioxide Exposure Levels in the Extravehicular Mobility Unit

Kyoung Jae Kim; Omar S. Bekdash; Jason R. Norcross; Johnny Conkin; Alejandro Garbino; John Fricker; Millennia Young; Andrew F. J. Abercromby

BACKGROUND: NASA has been making efforts to assess the carbon dioxide (CO_2) washout capability of spacesuits using a standard CO_2 sampling protocol. This study established the methodology for determining the partial pressure of inspired CO_2 (P_ICO_2) in a pressurized spacesuit. We applied the methodology to characterize P_ICO_2 for the extravehicular mobility unit (EMU).

METHODS: We suggested an automated and mathematical algorithm to find the end-tidal CO_2 and the end of inspiration. We provided objective and standardized guidelines to identify acceptable breath traces, which are essential to accurate and reproducible calculation of the in-suit inhaled and exhaled partial pressure of CO_2 (PCO_2). The mouth guard-based method for measurement of inhaled and exhaled dry-gas PCO_2 was described. We calculated all individual concentrations of P_ICO_2 inhaled by 19 healthy subjects classified into 3 fitness groups. The transcutaneous PCO_2 was monitored as a secondary measure to validate washout performance.

RESULTS: Mean and standard deviation values for the data collection performance and the CO_2 metrics were presented (e.g., minimum time weighted average PCO_2 at suited workloads of resting, 1000, 2000, and 3000 ($BTU \cdot h^{-1}$) were 4.75 ± 1.03, 8.09 ± 1.39, 11.39 ± 1.26, and 14.36 ± 1.29 ($mmHg \cdot s^{-1}$). All CO_2 metrics had a statistically significant association and all positive slopes with increasing metabolic rate. No significant differences in CO_2 metrics were found between the three fitness groups.

DISCUSSION: A standardized and automated methodology to calculate P_ICO_2 exposure level is presented and applied to characterize CO_2 washout in the EMU. The EMU has been operated successfully in over 400 extravehicular activities (EVAs) and is considered to provide acceptable CO_2 washout performance. Results provide a basis for establishing verifiable PCO_2 requirements for current and future EVA spacesuits.

KEYWORDS: inspired carbon dioxide (CO_2), CO_2 washout, extravehicular mobility unit (EMU) spacesuit, transcutaneous monitor.

Kim KJ, Bekdash OS, Norcross JR, Conkin J, Garbino A, Fricker J, Young M, Abercromby AFJ. *The partial pressure of inspired carbon dioxide exposure levels in the extravehicular mobility unit.* Aerosp Med Hum Perform. 2020; 91(12):923–931.

Exposure to carbon dioxide (CO_2) during spaceflight is of primary concern for NASA toxicologists, flight surgeons, and astronauts as the effects of exposure to elevated levels can negatively affect astronaut performance and long-term health.[7,8] The exact duration, dose, and attributable physiological effects, however, are highly variable and difficult to accurately predict. This uncertainty has led to a progressive lowering of vehicle and habitat exposure levels to help relieve some of the symptoms being reported by crewmembers that may be attributed to rising levels. These limits are intended to apply only to long-duration chronic exposures, in large habitat and vehicle volumes, and thus should not be applied to spacesuit exposures, where crewmembers may be acutely exposed to high levels of CO_2 in a confined helmet space.

Providing adequate CO_2 washout is essential to the reduction of risk in performing suited operations. Washout capability

From the NASA Johnson Space Center, Houston, TX, USA.

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Address correspondence to: Kyoung Jae Kim, KBR, 2400 NASA Parkway, Houston, TX 77058; kyoungjae.kim@nasa.gov.

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Link

Part 1. Determination of VT and RCP*

- *Exercise countermeasures*
  - The only known way for maintaining muscle mass, strength, and cardiorespiratory fitness in crewmembers during spaceflight
  - Important for exercise prescriptions to be optimized to maintain astronauts' fitness during performance of mission-critical tasks
  - A reliable detection method can help to quickly identify and guide individualized exercise prescriptions

➔ Proposed a novel automated method to provide valuable information regarding crewmembers' ability to exercise on the International Space Station and to perform Beyond Low Earth Orbit exploration objectives

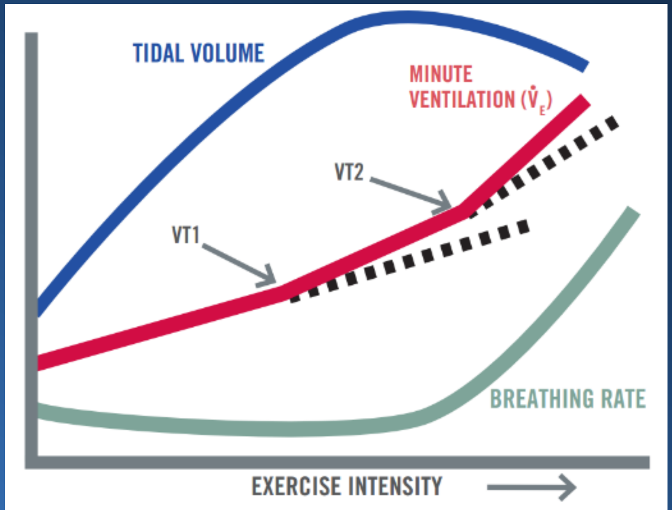
Credit: NASA

* VT: Ventilatory Threshold, RCP: Respiratory Compensation Point

Background

- *What to measure?*
  - The ventilatory profile during incremental exercise has been used to assess aerobic fitness and monitor and prescribe exercise training
  - Peak cycle test using a metabolic monitor (~15 min)
    - Oxygen uptake (VO_2)
    - Carbon dioxide production (VCO_2)

- *Two inflection points*
  - Ventilatory threshold (VT1)
    - Described as the intensity of activity that causes the first rise in the ventilatory equivalent of O_2
  - Respiratory compensation point (VT2)
    - Considered the second break point at the onset of hyperventilation (respiratory compensation) during incremental exercise



LODE Excalibur sport cycle ergometer (Lode BV, Groningen, Netherlands)*

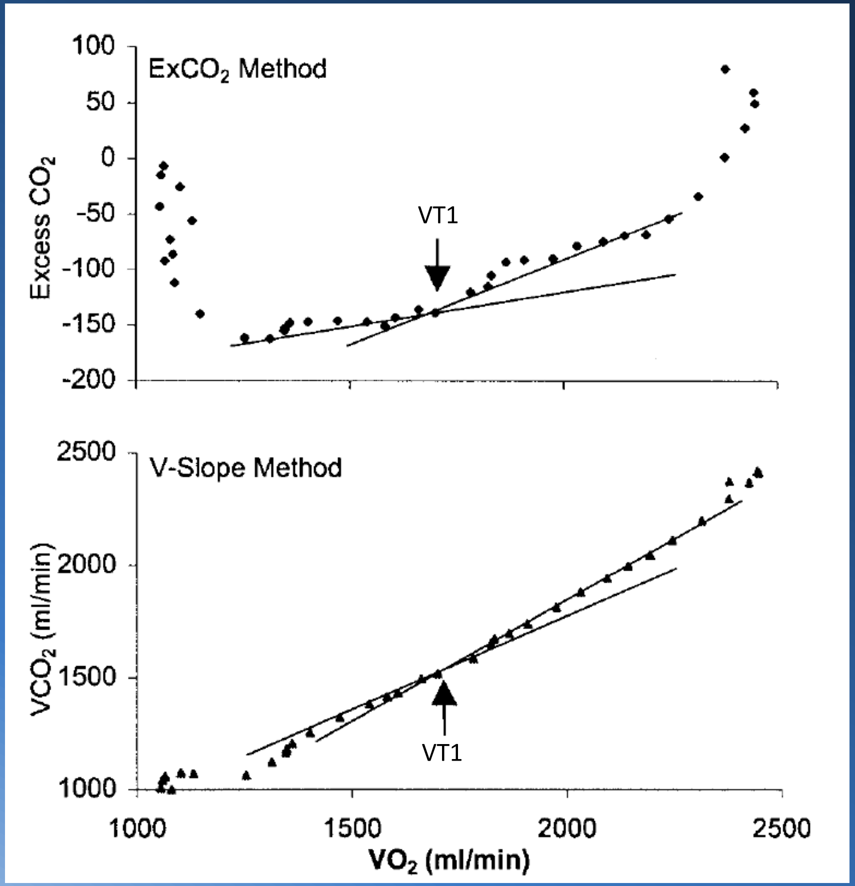
Credit: H-3PO

***Trademark Statement:**

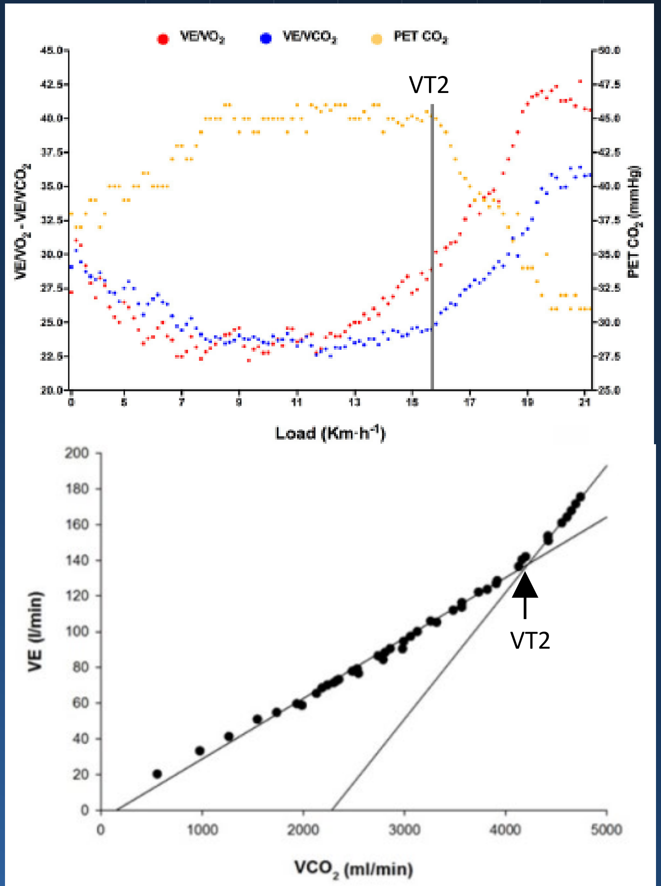
Trade names and trademarks are used in this journal article for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

Conventional Approaches

- *Conventional methods for VT1**
- *Conventional methods for VT2***



* Gaskill, S. E., et al., (2001). Validity and reliability of combining three methods to determine ventilatory threshold. *Medicine & Science in Sports & Exercise*.



PET CO2: end-tidal CO2

** Cerezuela-Espejo, V., et al. (2018). The relationship between lactate and ventilatory thresholds in runners: validity and reliability of exercise test performance parameters. Frontiers in Physiology. Korkmaz Eryılmaz, S., et al. (2018). The relationship between the isocapnic buffering phase and ventilatory threshold in endurance athletes and team sport athletes during an incremental exercise test. Annals of Applied Sport Science.

Proposed Computerized Determination

- *Code for the proposed approach using findchangepts**

Input:

```
VCO2: a vector with N elements (n×1) %% Rate of CO2 production Volume of CO2/min
VO2 : a vector with N elements (n×1) %% Rate of O2 Consumption Volume of O2/min
VE  : a vector with N elements (n×1) %% Minute ventilation Volume of expired air/min
```

Process:

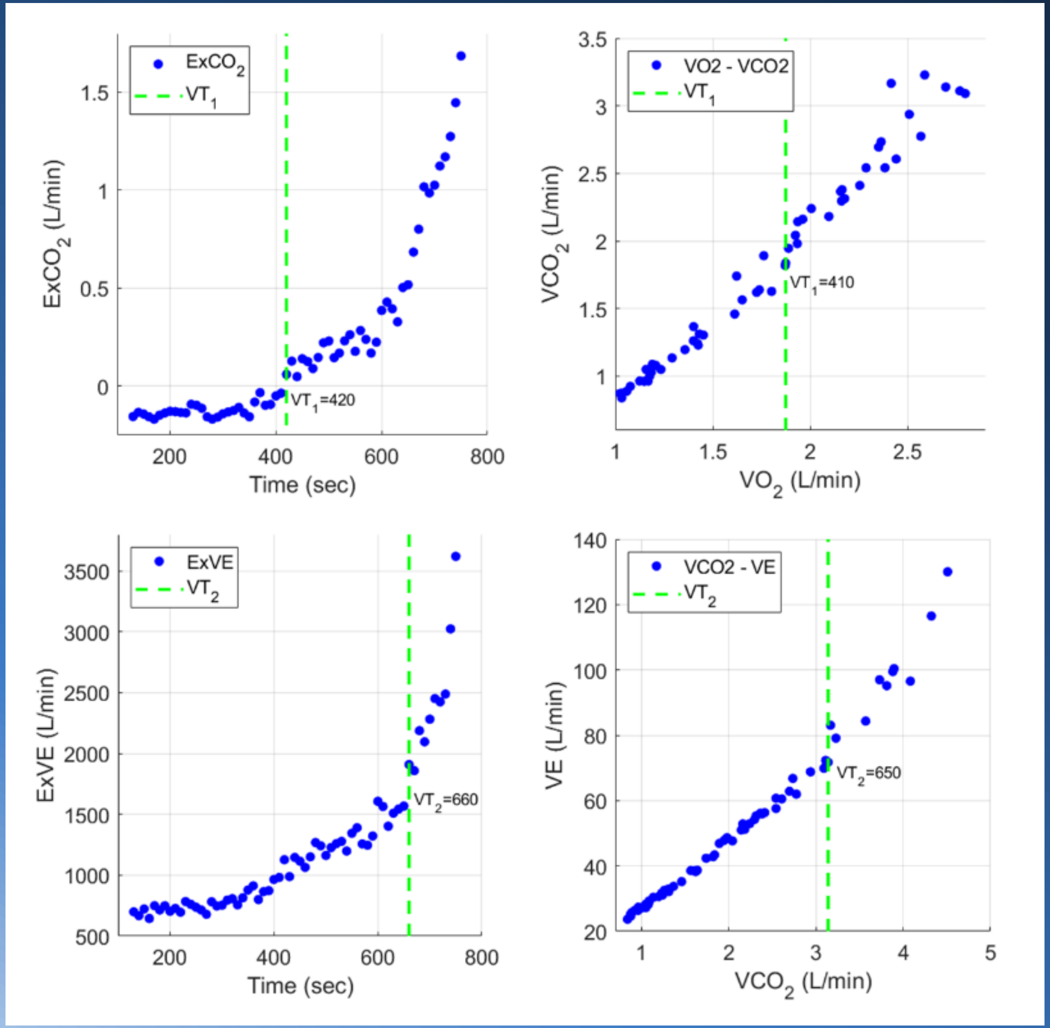
```
ExCO2 = ((VCO2 .* VCO2) ./ VO2) - VCO2 %% Excess carbon dioxide method (VT1)
ipt_ExCO2= findchangepts(ExCO2, 'Statistic', 'std', 'MaxNumChanges', 1)
Vslope1 = [VO2 VCO2]' %% V-slope (VT1)
ipt_Vslope1 = findchangepts(Vslope1, 'Statistic', 'std', 'MaxNumChanges', 1)
ExVE = ((VE .* VE) ./ VCO2) - VE %% Excess minute ventilation method (VT2)
ipt_ExVE = findchangepts(ExVE, 'Statistic', 'std', 'MaxNumChanges', 1)
Vslope2 = [VCO2 VE]' %% V-slope (VT2)
ipt_Vslope2 = findchangepts(Vslope2, 'Statistic', 'std', 'MaxNumChanges', 1)
vt1 = round((ipt_ExCO2 + ipt_Vslope1) / 2)
vt2 = round((ipt_ExVE + ipt_Vslope2) / 2)
```

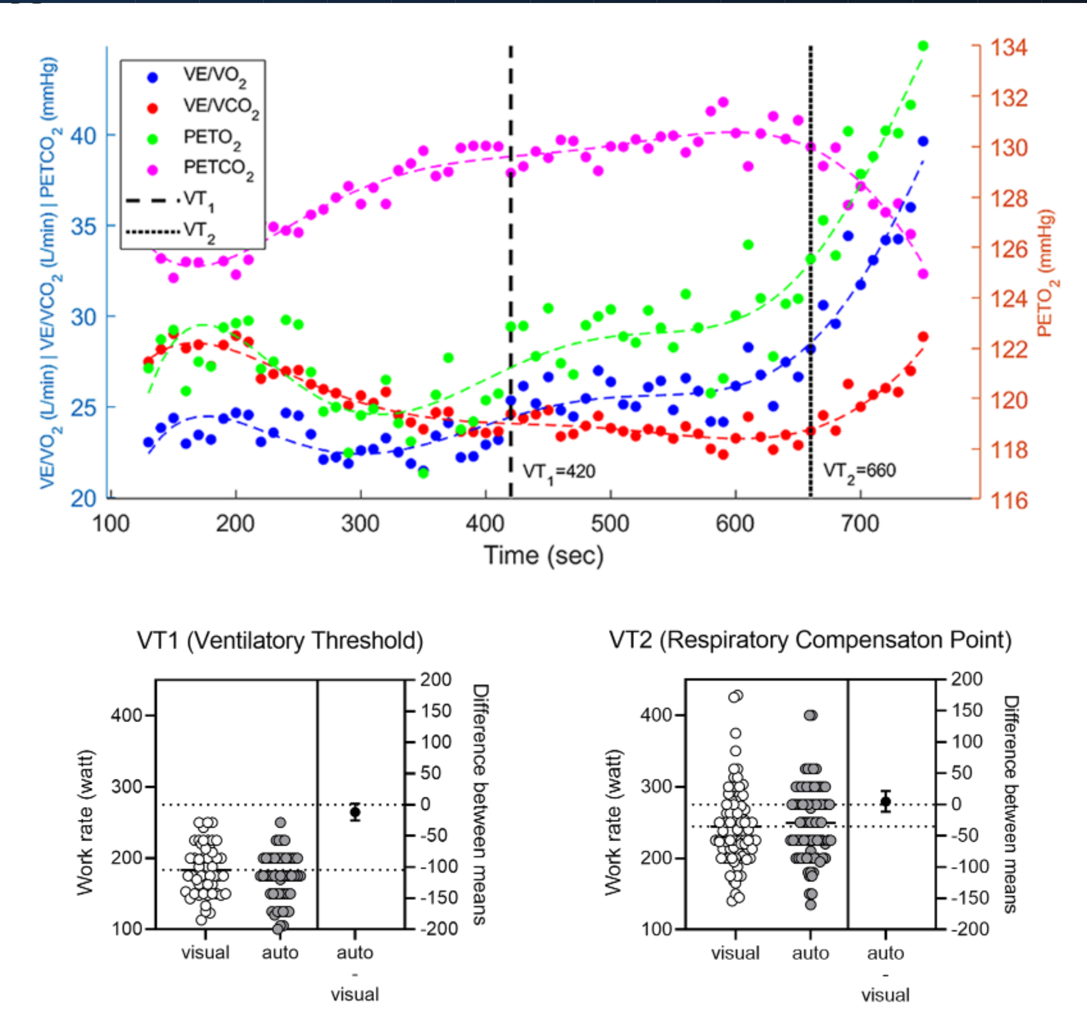
Output:

```
ipt_ : Changepoint locations
vt1  : Ventilation threshold (VT1) location
vt2  : Respiratory compensation point (VT2) location
```

* Killick, Rebecca, Paul Fearnhead, and Idris A. Eckley. (2012) Optimal detection of changepoints with a linear computational cost." Journal of the American Statistical Association.
Lavielle, Marc. (2005) Using penalized contrasts for the change-point problem. Signal Processing.

Proposed Computerized Determination

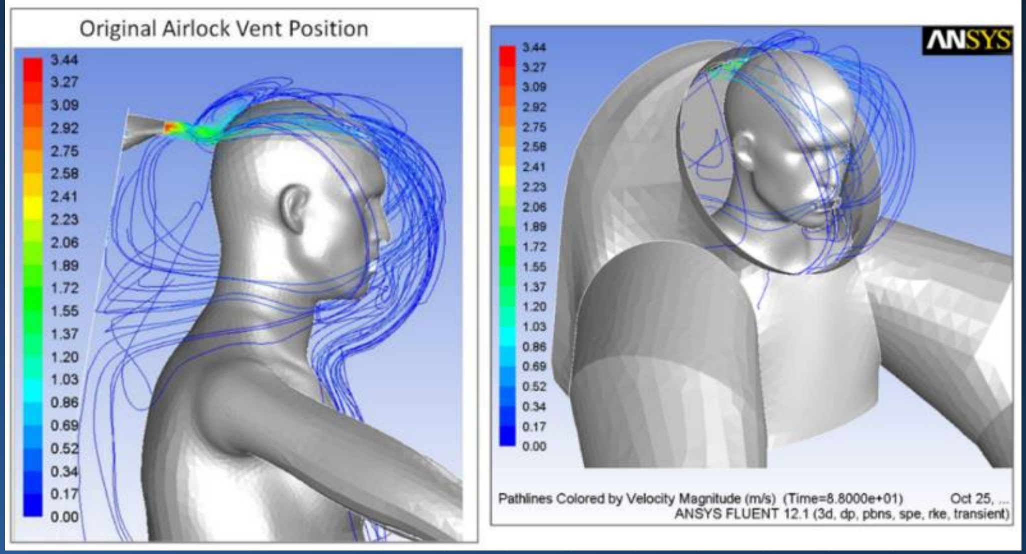




ExVE: Excess minute ventilation

Part 2. Calculation of Inspired CO_2

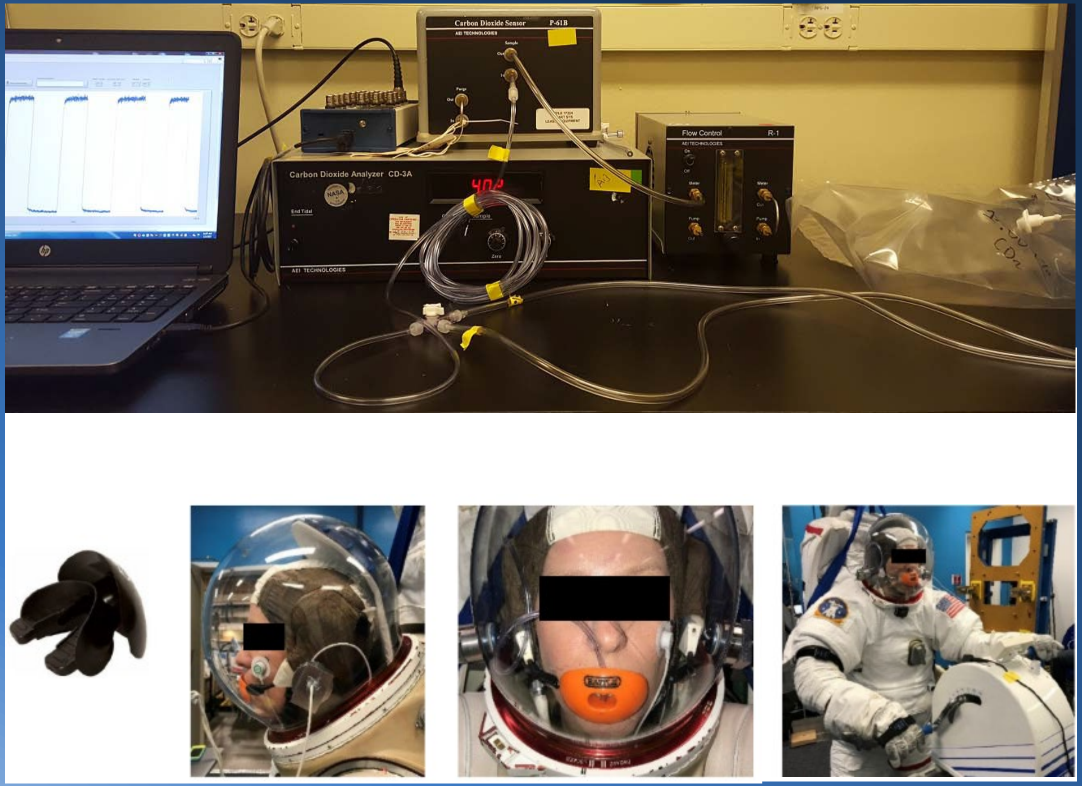
- CO_2 can build up quickly inside an enclosed environment if proper ventilation is not in place
- Acute health effects of high CO_2 exposures include:
  - Headache, dizziness, shortness of breath, sweating, increased blood pressure, unconsciousness, death
- Maintaining adequate CO_2 washout during EVA or ground-based suit testing is critical to crew and subject safety
- "Inspired CO_2" is the term for what level of CO_2 actually enters a person's oral/nasal passages when breathing in



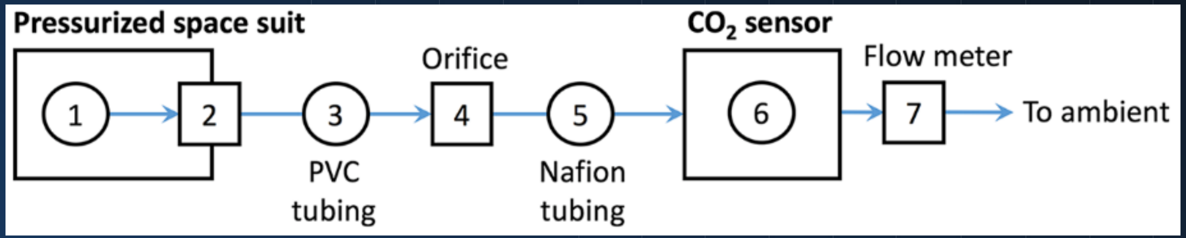
Computational fluid dynamics flow patterns resulting from Z1 suit evaluation
Chullen, Cinda et al., (2013) Maintaining adequate carbon dioxide washout for an advanced extravehicular mobility unit. *International Conference on Environmental Systems (ICES)*

Quantification of CO_2 washout of suit

- Standard hardware set up for in-suit measurement of CO_2



Credit: H-3PO



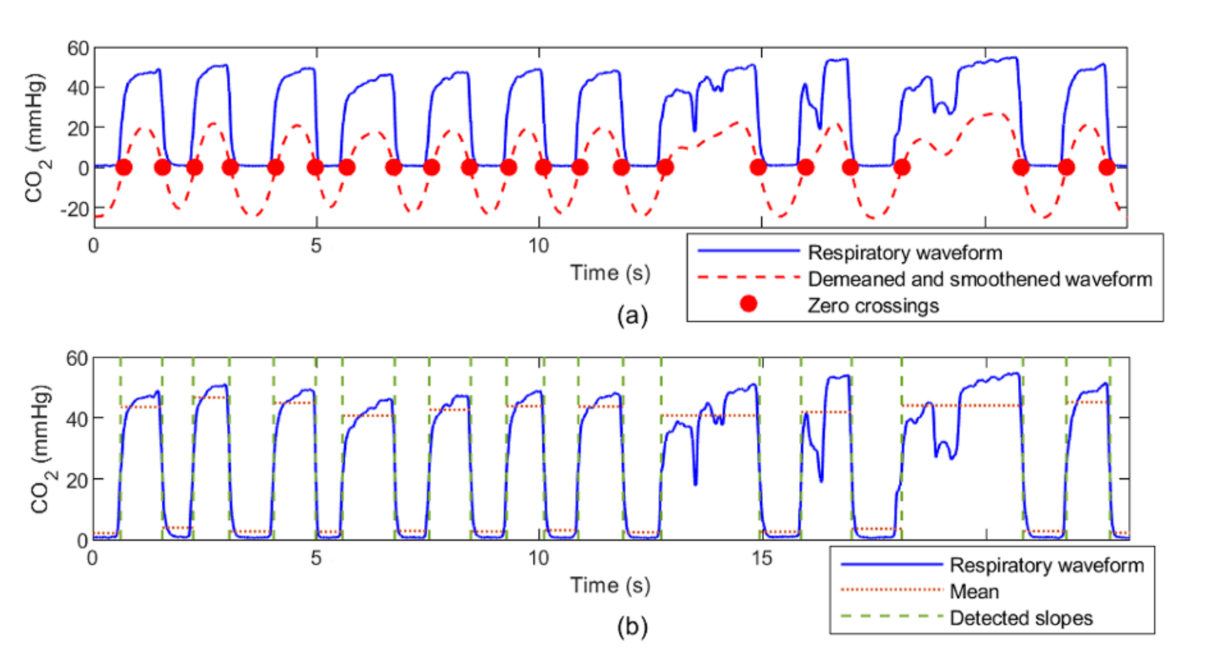
Air sampling configuration*

1. Mouth guard sample probe;
2. Suit pass-through port;
3. 10-ft, 1/16-in ID Tygon PVC tubing;
4. Orifice sized to achieve 1000 ml · min^{-1} to sensor;
5. Nafion tubing;
6. Infrared CO_2 sensor, AEI Technologies CD-3A;
7. Flow meter for sample flow rate verification.

* Bekdash O, Norcross J, Fricker J, Meginnis I, Abercromby A. Characterization of variability sources associated with measuring inspired CO2 in spacesuits. *IEEE Aerospace Conference*; 2017 Mar 4-11; Big Sky, MT.
Bekdash O, Fricker J, Kim KJ, Conkin J, Meginnis I, Norcross J, Abercromby A. Standard testing procedure for quantifying breathing gas carbon dioxide partial pressure for extravehicular activity and launch, entry, survival pressure suits. *NASA Technical Report*; NASA/TM-2020-220525:1-24

Quantification of CO_2 washout of suit

- Finding changepoints (*findchangepts* employs a parametric global method)



findchangepts finds k such that

$$J(k) = \sum_{i=1}^{k-1} \Delta\left(x_i; \chi\left(\left[x_1 \quad \cdots \quad x_{k-1}\right]\right)\right) + \sum_{i=k}^{N} \Delta\left(x_i; \chi\left(\left[x_k \quad \cdots \quad x_N\right]\right)\right)$$

is smallest, given the section empirical estimate χ and the deviation measurement Δ.

Generalizing the procedure is straightforward when the number of changepoints is known. If there are K changepoints to be found, then the function minimizes

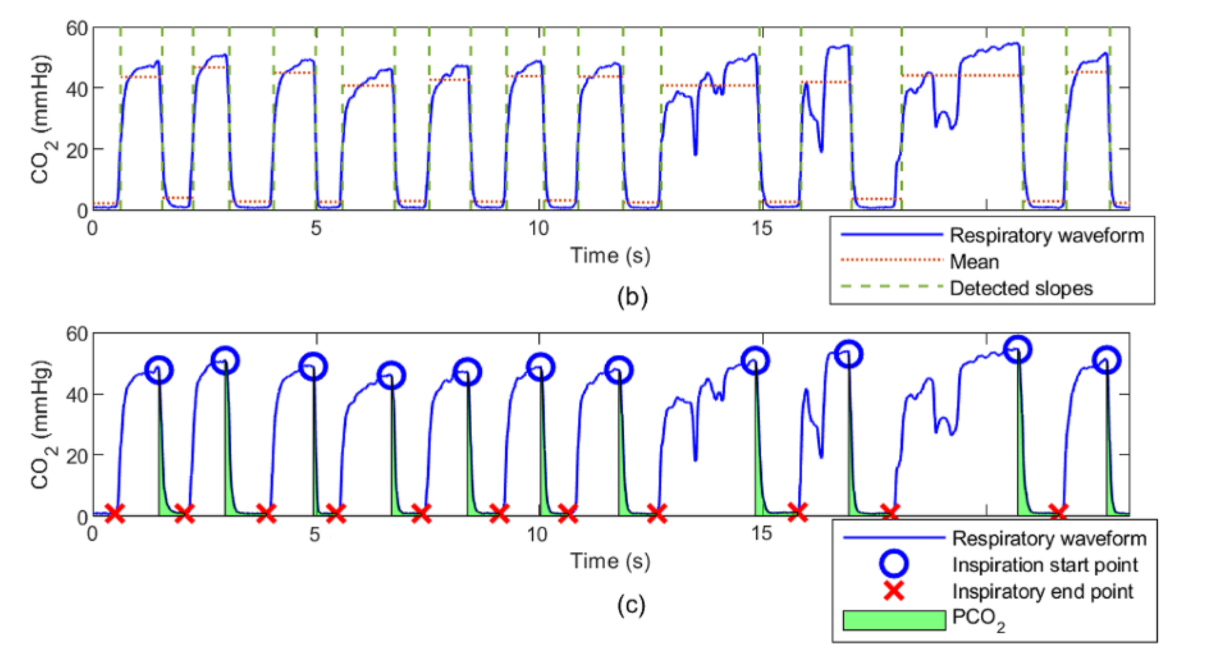
$$J(K) = \sum_{r=0}^{K-1} \sum_{i=k_r}^{k_{r+1}-1} \Delta\left(x_i; \chi\left(\left[x_{k_r} \quad \cdots \quad x_{k_{r+1}-1}\right]\right)\right) + \beta K,$$

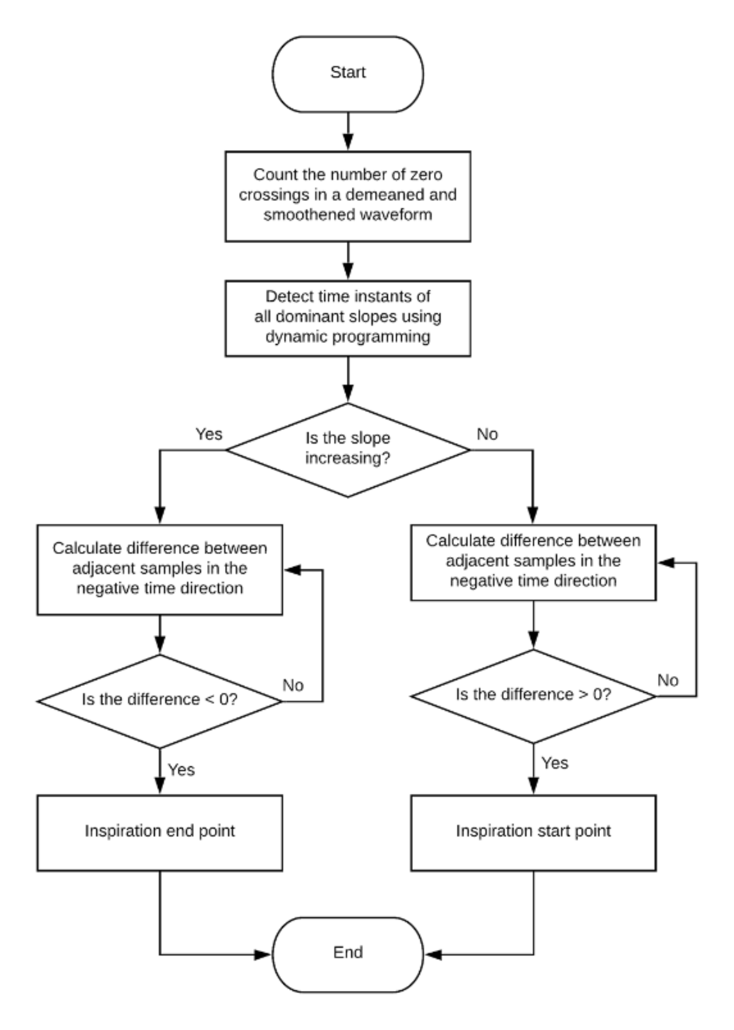
where k_0 and k_K are respectively the first and the last sample of the signal.*

* Killick, Rebecca, Paul Fearnhead, and Idris A. Eckley. (2012) Optimal detection of changepoints with a linear computational cost." Journal of the American Statistical Association.
Lavielle, Marc. (2005) Using penalized contrasts for the change-point problem. Signal Processing.

Quantification of CO_2 washout of suit

- Finding inspiration start and end points





Future Plan

- Ventilatory threshold and respiratory compensation point determination in R with an interactive application
  - https://cran.r-project.org/web/packages/changepoint/changepoint.pdf

- Real-time calculation of inspired CO_2

- Other applications of change point detection methods
  - Real-time gait analysis
  - Repetitive or incremental exercise data
  - Etc.

Thank you.

KJ Kim, Ph.D.
Contact: kyoungjae.kim@nasa.gov