Entropy Change Index as a Measure of Cardio-Thermal Physiological Stress Response

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ABSTRACT

The present study describes the application of a thermodynamics-based entropy approach to model and measure human cardio-thermo-physiological stress response. Using Maxwell relations, this approach combines three physiological measures (blood pressure, heart rate, and core body temperature) to provide a quantitative measure of cardio-thermal stress response in terms of entropy change. This entropy change expression provides a mathematical link between cardiovascular and thermoregulatory responses based on the principles of thermodynamics. The experimental data was obtained from a NASA Johnson Space Center study involving seven subjects to demonstrate this methodology. The three physiological measures were taken under four conditions (Rest, 40% $VO_{2\ peak}$, 65% $VO_{2\ peak}$, and Recovery) in five-minute intervals during the course of the entire eighty-minute physiological test. The entropy change computed from the experimental data was normalized to obtain an entropy change index (ECI). Further, it is statistically established that ECI could be used in addition to individual measures such as blood pressure, heart rate, and core body temperature to assess human stress response and performance.

Keywords **–** cardio-thermal physiology; entropy change index; stress; thermodynamics.

1. INTRODUCTION

Several studies have made significant efforts to quantify human cardio-thermal physiological stress response. Most of these earlier studies examine physiological strain or stress response using a single or at most two physiological indicators. In an experimental study conducted by Moran et al. [1] combines two physiological responses including core body temperature and heart rate, to develop a *Physiological Strain Index (PSI).* The limitation of PSI is that it is statistically based and empirical in nature, which limits its application to specific populations and measurement of heat stress. Since the human cardio-thermal physiological system consists of many interconnected physiological processes controlled by a complex nervous system, single physiological indicators provide a very narrow representation of the human response system. It is only by recognizing the interaction among human subsystems in their response to any stimuli that one could begin the investigation of human physiological responses. In this regard, the studies conducted by Boregowda et al. [2, 3] and Palsson et al. [4] have made an effort to develop an *Entropy Change Index (ECI)* that utilizes three physiological variables such as blood pressure, heart rate, and core body temperature. It is postulated that the entropy change in a living system is nothing but increased physiological disorder. The Maxwell relations are used to quantify abstract entropy change in terms of multiple measurable quantities such as pressure, volume, temperature, and electro-magnetic fields [5, 6]. An analogy between physical and human physiological systems is conceptualized and the properties of a non-living system are mapped to that of a living system. In this regard, the physical fluid-thermal system characterized by pressure (P), volume (V), and temperature (T) are directly mapped to that of a living human cardio-thermal physiological system's blood pressure (BP), heart rate (HR), and core body temperature level (CBT), respectively.

2. MODELING AND FORMULATION

In the scope of the present study, the cardiovascular and thermoregulatory systems which are responsible for the responses such as blood pressure (BP), heart rate (HR), and core body temperature (CBT) are considered in the thermodynamic analysis. In an earlier study [3], the physiological responses were taken under static conditions at only three different time intervals. However, the present study utilizes the NASA experimental data, which contains continuous physiological responses in five-minute intervals for a total of eighty minutes. This study provides an opportunity to examine the variation of entropy change on a moment-to-moment basis and thereby provides a better view of cardio-thermoregulatory response to stress.

The philosophical approach behind the present study is based on the premise established by Harvard Physicist P.W. Bridgman [7], who stated that - *"It must be admitted. I think, that laws of thermodynamics have a different feel from most other laws of physics. There is something more palpably verbal about them – they smell more of their human origin…"* It is observed that the human cardio-thermo-physiological system is regarded as an open thermodynamic system that exchanges energy and matter with the surroundings. It has been shown that the increased disorder (or change in entropy) in a cardio-thermo-physiological system in response to any stressor is defined to be mathematically equivalent to the Entropy change index (ECI) and is stated under Postulate I as follows:

Postulate I. The normalized entropy which represents the ratio of the entropy change (ΔS) in a cardio-thermo-physiological system of interest during the resting state and stressor to that of resting state (average entropy change, $(\Delta S)_{Avg.\ Rest}$, during rest) is expressed as an Entropy change index (ECI).

As shown in Equations (1), if the cardio-thermo-physiological responses, which include blood pressure (BP), heart rate (HR), and core body temperature (CBT) are equivalent to pressure (P), volume (V), and temperature (T) in a fluid-thermal system, then the entropy is written as follows:

Physical Entropy = f {Pressure, Volume, and Temperature} (1a)

Physiological Entropy = f {Blood Pressure, Heart Rate, and Core Body Temperature} (1b)

By applying the Maxwell relations of thermodynamics to model the human cardio-thermo-physiological system, the (ECI) is calculated as follows:

$$(\Delta S) = [(BP-BP_O) \times (HR-HR_O)] / [CBT-CBT_O] \quad (2)$$

$$(\Delta S)_{Avg.\ Rest} = [(BP_{Avg.\ Rest}-BP_O) \times (HR_{Avg.\ Rest} - HR_O)] / [CBT_{Avg.\ Rest}-CBT_O] \quad (3)$$

$$ECI = (\Delta S) / (\Delta S)_{Avg\ Rest} \quad (4)$$

Where, ECI = entropy change index for cardio-thermal physiological system, dimensional units
BP = blood pressure (systolic or diastolic), mm Hg
HR = heart rate, beats per minute
CBT = core body temperature (average of esophageal, rectal, and intestine temperatures), ^{0}C
$BP_O = HR_O = ST_O = 0$ (Reference States)
$BP_{Avg.\ Rest}$ = average blood pressure (systolic or diastolic) during the resting state (20 minutes)
$HR_{Avg.\ Rest}$ = average heart rate during the resting state (20 minutes)
$CBT_{Avg.\ Rest}$ = average core body temperature during the resting state (20 minutes)

It is restated that normalized entropy change in the form of an entropy change index (ECI) could be postulated as a physiological reflection of a disorder and thus a measure of physiological stress as per Postulate II.

Postulate II: The non-dimensional entropy change, a measure of disorder in a human cardio-thermal physiological system and is equivalent to cardio-thermal physiological stress response.

ECI = f {BP, HR, and CBT} ≡ Cardio-Thermal Physiological Stress Response (5)

3. METHODS

The data was obtained from a NASA experimental study conducted by Lee et al. [8] involving seven subjects who participated in the investigation. Subjects completed a health screening, which was administered by a qualified physician in the NASA-Johnson Space Center Human Test Subject Facility. Testing procedures were reviewed and approved by the NASA-Johnson Space Center Institutional Review Board. Subjects completed a supine graded exercise test on a cycle ergometer to determine peak oxygen consumption (VO_{2pk}) in this posture. From these data, exercise intensities corresponding to 40% and 65% of supine VO_{2pk} were determined for use during the subsequent submaximal exercise test. During the exercise tests, simultaneous measurements of core body temperatures (esophageal, rectal, and intestinal temperatures), blood pressure, and heart rate were made.

4. RESULTS AND ANALYSIS

Please refer to **Appendix A** for an illustrative example followed by figures and tables in **Appendix B**. The monitoring of entropy change index (ECI) is shown in Figures 1 and 2. Figure 1 depicts the entire time-series systolic blood pressure-based ECI data for all seven subjects. Similarly, the variation diastolic blood pressure-based ECI data is shown in Figure 2. It is clear from these figures that there are individual differences in how subjects respond to different levels of exercise.

A descriptive statistical analysis is conducted on each of the data streams pertaining to all seven subjects. The ECI statistical measures such as mean and standard deviation are computed for each of the subjects under four conditions. These conditions include - resting state, 40% $VO_{2\ peak}$, 65% $VO_{2\ peak}$, and recovery. The data are shown in Tables 2 and 3 for $(ECI)_{SBP}$ and $(ECI)_{DBP}$, respectively. The data shown in Tables 2 and 3 are shown graphically in Figures 3 and 4. These figures reflect individual variation in mean response to four different exercise conditions. It clearly shows that there is more variation among subjects during the exercise conditions of 40% $VO_{2\ peak}$ and 65% $VO_{2\ peak}$. The resting state and recovery do not indicate any variation in stress responses. The entropy change index (ECI) provides a holistic measure of human cardio-thermal stress response to varying exercise conditions. Using ECI, the human performance analysts could develop a scale to measure the level of physiological condition of athletes, astronauts, fire fighters, police, military personnel, and other emergency personnel who perform their tasks in extreme environments.

5. Conclusion

The results from this study offer some preliminary indications suggesting that the entropy change index (ECI) could be used as an index to measure the levels of physiological stress response to varying exercise conditions. Data from a NASA experimental study was used to validate the proposed Entropy change index (ECI) as a measure of cardio-thermal physiological stress response. The descriptive statistical results indicate that the ECI holds a promise as a metric to measure and evaluate human physiological stress, performance, and levels of conditioning. The combined measure of ECI provides a systems view of varying levels of physiological conditioning. Thus, the engineering thermodynamics-based ECI is would provide the fields of medicine and health sciences with something which has long been sorely missing - a scientifically sound and useful way of quantifying human cardio-thermal physiological stress response as a single number.

Acknowledgements

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APPENDIX A: ILLUSTRATIVE EXAMPLE

This section contains a sample calculation of the entropy change index in a stepwise manner. Each one of the physiological measures - BP, HR, and CBT, used in the calculation of entropy change indices, pertain to subject #1. Let us consider subject#1, whose physiological stress response values during the resting state are given in Table 1.

Table 1: Average Values of Physiological Responses during the Resting State

Time (Min)	TES	TREC	TIN	HR	SBP	DBP
0.00	37.08	37.10	37.26	55.00	104.00	65.00
5.00	37.03	37.00	37.21	67.00	102.00	68.00
10.00	37.08	37.00	37.19	55.00	105.00	65.00
15.00	37.03	36.95	37.16	55.00	103.00	65.00
20.00	36.97	36.90	37.10	58.00	100.00	64.00
Average	37.04	36.99	37.18	58.00	102.80	65.40

The average value of the entropy change during the resting state is given by Eq (3) and is rewritten by replacing $BP_{Avg.\ Rest}$ with the Systolic Blood Pressure ($SBP_{Avg.\ Rest}$) as follows:

$$(\Delta S)_{Avg.\ Rest} = [(SBP_{Avg.\ Rest} - SBP_O) \times (HR_{Avg.\ Rest} - HR_O)] / [CBT_{Avg.\ Rest} - CBT_O]$$

Where, $SBP_{Avg.\ Rest}$ = 102.80 mm Hg
$HR_{Avg.\ Rest}$ = 58.00 bpm

$CBT_{Avg. Rest}$ = 36.99 0C
$SBP_O = HR_O = CBT_O$ = 0 (Reference states)

By substituting the above values of physiological variables in Eq (7), we get,

$(\Delta S)_{Avg. Rest}$ = [(102.80 – 0.0) x (58.00 - 0.00)] / [36.99 – 0.0] = 161.19 mm Hg.bpm/oC

The change in entropy during the stressor (rest and exercise) using systolic blood pressures is computed by rewriting the Eq. (2) with systolic blood pressure for the entire time series (at five-minute intervals). For the sake of brevity, the calculations are shown at 0th,…, 20th,…40th,…60th,…80th minutes as follows:

(ΔS) = [(SBP-SBPO) x (HR-HRO)] / [CBT-CBTO]

(ΔS) SBP, 0,min = [(104.00 – 0.0) x (55.00 - 0.00)] / [37.10 – 0.0] = 154.19 mm Hg.bpm/oC
:
(ΔS) SBP, 20,min = [(100.00 – 0.0) x (58.00 - 0.00)] / [36.90 – 0.0] = 157.18 mm Hg.bpm/oC
:
(ΔS) SBP, 40,min = [(134.00 – 0.0) x (92.00 - 0.00)] / [37.10 – 0.0] = 332.29 mm Hg.bpm/oC
:
(ΔS) SBP, 60,min = [(165.00 – 0.0) x (112.00 - 0.00)] / [37.46 – 0.0] = 493.33 mm Hg.bpm/oC
:
(ΔS) SBP, 80,min = [(118.00 – 0.0) x (63.00 - 0.00)] / [37.36 – 0.0] = 198.98 mm Hg.bpm/oC

The systolic blood pressure-based entropy change index (ECI) SBP is calculated accordingly as follows:

(ECI)SBP, 0 min = (ΔS)SBP, 0 min / (ΔS) Avg. Rest = 154.19 / 161.19 = 0.96
:
(ECI)SBP, 20 min = (ΔS)SBP, 20 min / (ΔS) Avg. Rest = 157.18 / 161.19 = 0.98
:
(ECI)SBP, 40 min = (ΔS)SBP, 40 min / (ΔS) Avg. Rest = 332.29 / 161.19 = 2.06
:
(ECI)SBP, 60 min = (ΔS)SBP, 60 min / (ΔS) Avg. Rest = 493.33 / 161.19 = 3.06
:
(ECI)SBP, 80 min = (ΔS)SBP, 80 min / (ΔS) Avg. Rest = 198.98 / 161.19 = 1.23

In a similar manner, the rest of the $(ECI)_{SBP}$ are computed for the remaining six subjects. Similarly, the $(ECI)_{DBP}$ values are computed for the all seven subjects and the results are provided in the results and analysis section and corresponding figures and tables are provided in the next Appendix B.

APPENDIX B: FIGURES AND TABLES (Refer to Section 4 on RESULTS AND ANALYSIS)

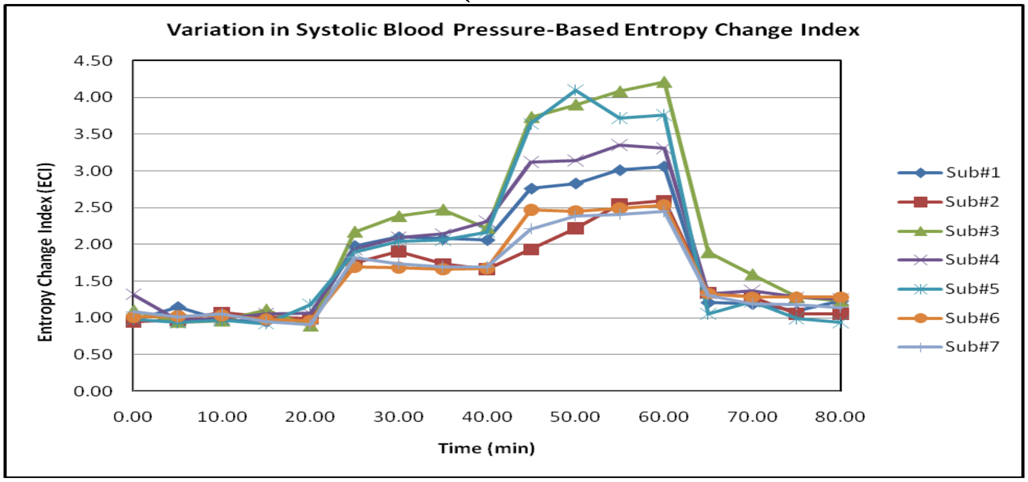

Figure 1. Continuous Monitoring of $(ECI)_{SBP}$

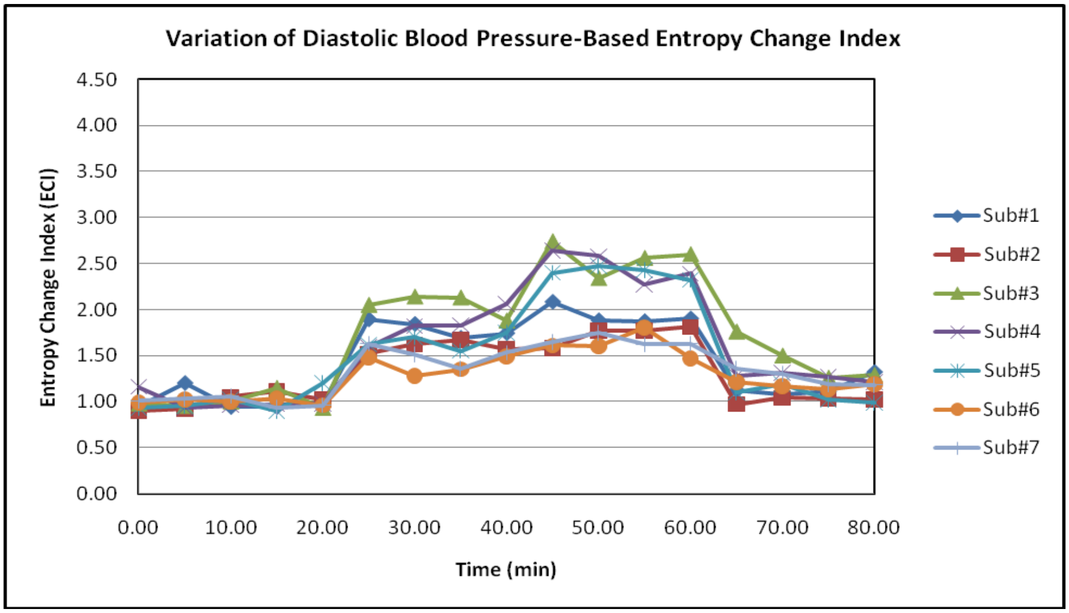

Figure 2. Continuous Monitoring of $(ECI)_{DBP}$

Table 2: Average $(ECI)_{SBP}$ Values under Four Exercise Conditions

Subjects	Resting State		40% VO2 Peak		65% VO2 Peak		Recovery	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	1.00	0.08	2.05	0.05	2.91	0.15	1.18	0.06
2	1.00	0.05	1.76	0.10	2.32	0.31	1.18	0.15
3	1.00	0.10	2.31	0.14	3.98	0.21	1.50	0.31
4	1.08	0.14	2.12	0.16	3.23	0.12	1.30	0.05
5	1.00	0.10	2.04	0.12	3.81	0.20	1.05	0.12
6	1.00	0.03	1.68	0.01	2.48	0.04	1.29	0.02
7	1.00	0.07	1.74	0.06	2.36	0.10	1.20	0.08

Table 3: Average (ECI) $_{DBP}$ values under Four Exercise Conditions

Subjects	Resting State		40% VO2 Peak		65% VO2 Peak		Recovery	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	1.00	0.11	1.79	0.09	1.93	0.10	1.16	0.11
2	1.00	0.09	1.59	0.06	1.73	0.10	1.02	0.03
3	1.00	0.09	2.05	0.12	2.56	0.16	1.45	0.23
4	1.08	0.09	1.83	0.19	2.47	0.17	1.27	0.04
5	1.00	0.12	1.65	0.09	2.40	0.06	1.07	0.09
6	1.00	0.02	1.40	0.10	1.62	0.13	1.17	0.04
7	1.00	0.05	1.51	0.11	1.66	0.06	1.25	0.09

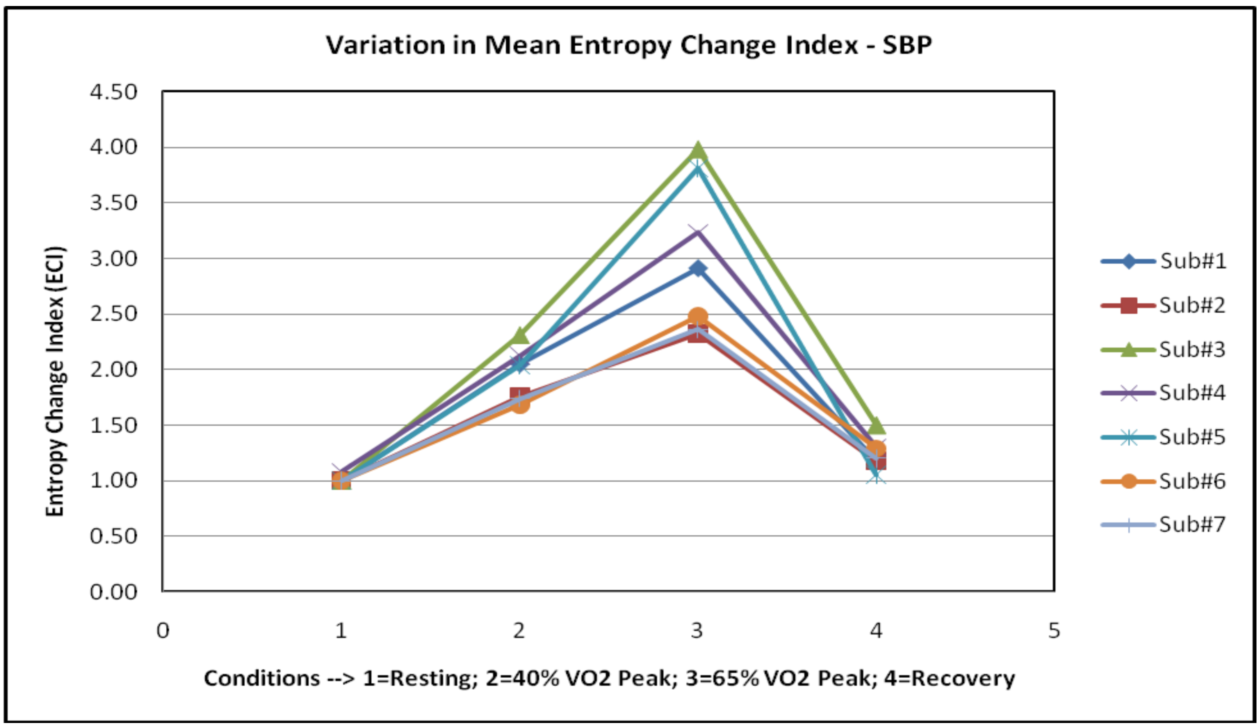

Figure 3. Monitoring of Mean (ECI) $_{SBP}$ – Indicates Individual Variation

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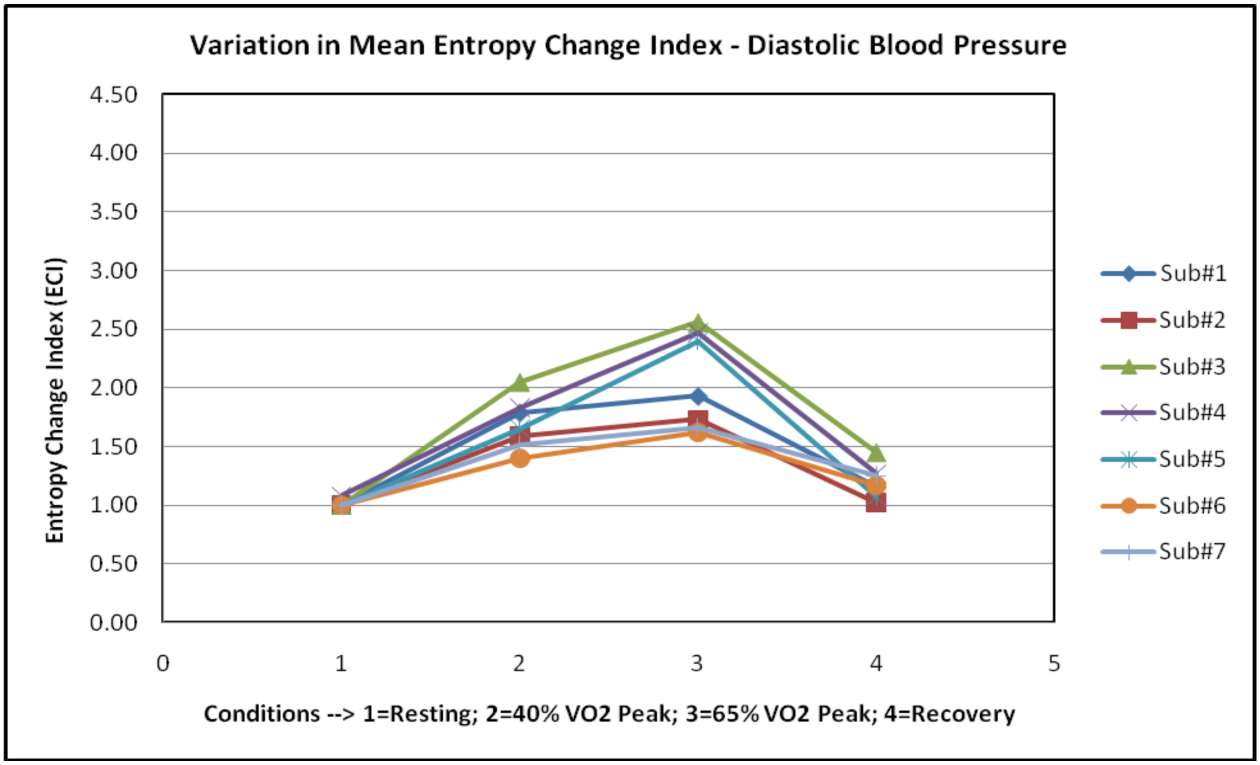

Figure 4. Monitoring of Mean (ECI) $_{DBP}$ – Indicates Individual Variation