Cardiovascular and thermoregulatory biomarkers of heat stroke severity in a conscious rat model

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Quinn CM, Duran RM, Audet GN, Charkoudian N, Leon LR. Cardiovascular and thermoregulatory biomarkers of heat stroke severity in a conscious rat model. J Appl Physiol 117: 971–978, 2014. First published August 14, 2014; doi:10.1152/japplphysiol.00365.2014.—Multiorgan failure is a catastrophic consequence of heat stroke (HS) and considered the underlying etiology of mortality. Identifying novel biomarkers capable of predicting the extent of HS-induced organ damage will enhance point-of-care triage and treatment. Conscious male F344 rats (n = 32) were radiotelemetered for continuous core temperature (Tc), heart rate, and arterial pressure measurement. Twenty-two animals were exposed to ambient temperature of 37°C to a maximum Tc of 41.9 ± 0.1°C. Rats were euthanized at 24 h of recovery for analysis of plasma biomarkers [cardiac troponin I (cTnI), blood urea nitrogen (BUN), alanine aminotransferase (ALT), albumin, glucose] and histology. Tc profiles observed during recovery stratified HS severity into Mild, Moderate, and Severe. Eleven (50%) animals exhibited an acute compensatory hemodynamic response to heat exposure and a monophasic Tc profile consisting of sustained hyperthermia (~1°C). Five (23%) rats displayed hemodynamic challenge and a biphasic Tc profile with rapid return to baseline followed by rebound hyperthermia. All biomarkers were significantly altered from control values (P < 0.05). Four (18%) animals exhibited significant hemodynamic compromise during heat and a triphasic profile characterized by rapid cooling to baseline Tc, rebound hyperthermia, and subsequent hypothermia (~35°C) through 24 h. cTnI showed a 40-fold increase over CON (P < 0.001) and correlated with BUN (r = 0.912) consistent with cardiorenal failure. Hypoglycemia correlated with ALT (r = 0.824) suggestive of liver dysfunction. Histology demonstrated myocardial infarction, renal tubular necrosis, and acute liver necrosis. Two (9%) animals succumbed during HS recovery. This study identified novel biomarkers that predict HS severity and organ damage during acute recovery that could provide clinical significance for identifying key biomarkers of HS pathogenesis.

heat stroke; hemodynamic; thermoregulation; cardiac troponin I

HEAT STROKE (HS) is a debilitating illness characterized by myriad thermoregulatory, cardiovascular, and systemic inflammatory abnormalities whose severity and time course vary between individuals subjected to the same environmental conditions. Sustained exposure to uncompensable heat stress results in HS which manifests as profound central nervous system dysfunction, often complicated by coagulopathies and catastrophic multiorgan failure.

Several animal models have been developed in an effort to experimentally induce the pathogenesis and clinical manifestations of HS sequelae. Previously, our laboratory developed a mouse HS model that minimized the confounding influences of anesthesia and restraint on HS responses (16). This was accomplished using radiotelemetry in conscious, freely moving mice. This model has contributed importantly to our understanding of the pathophysiology of HS (9, 15, 17); however, the small animal size prevented instrumentation for measurement of physiological changes beyond core temperature [Tc; e.g., heart rate (HR), ECG, blood pressure] that are known to be altered during extreme heat exposure.

The pathophysiology of HS includes major cardiovascular involvement, which has been well documented for decades (4, 8, 13, 14, 21, 26–30, 33, 35). However, no controlled study in a conscious animal model has used cardiovascular parameters as predictive indexes of HS severity or as a correlate for prognostication. In addition to providing potential biomarkers of HS severity and prognosis, alterations in hemodynamic stability could provide key insights into the pathogenesis of this condition.

The goal of the present study was to expand the conscious rodent model of HS to the rat, enhancing the connection between experimental and clinical symptomatology by exploiting the larger body size and greater blood volume relative to the mouse. We sought to determine if differences in pathophysiological and thermoregulatory responses exist between the rat and mouse models. Additionally, we tested the central hypothesis that hemodynamic indexes can experimentally predict HS severity with greater accuracy than Tc and expose interindividual variability as an essential component of heat responsiveness.

METHODS

Animals

Thirty-two adult male Fischer 344 rats (Charles River Laboratories, Wilmington, MA) weighing 272.4 ± 4.7 g were used. Rats were housed individually in Nalgene polycarbonate cages (Ancare, Belford, NY) fitted with HEPA-filter cage tops and ALPHA-dri/Cob blend bedding (PharmaServ, Framingham, MA). Environmental enrichment consisted of a rat igloo (Nalgene Nunc, Rochester, NY), a maplewood product containing a food treat to encourage foraging (W0002, BioServ, Frenchtown, NJ), and stainless steel rings for the support of postural adjustments. Rats were housed under standard laboratory conditions (20 ± 2°C, 12:12-h light:dark cycle; lights on at 0600) in an Association for Assessment and Accreditation of Laboratory Animal Care-accredited facility. Rodent laboratory chow (Harlan Teklad, LM-485, Madison, WI) and water were provided ad libitum except during heat exposure. The Institutional Animal Care and Use Committee approved all experimental procedures, which were performed in accordance with the American Physiological Society’s guiding principles for research involving animals and adhered to the Guide for the Care and Use of Laboratory Animals.

Radiotelemetry Measurements

Ten days prior to arrival, rats were implanted intraperitoneally with TL11M2-C50-PXT Physiotel Multiplex Radiotelemetry Transmitters...
(Data Sciences International, St. Paul, MN) by Charles River Laboratory. Briefly, an abdominal midline incision was made, exposing the abdominal aorta. Aortic blood flow was temporarily restricted and a small incision made into the vessel through which a catheter was fed for systolic blood pressure (SBP) measurements. The abdominal aortic catheter was secured by a cellulose patch using medical glue, and aortic blood flow was then restored. The radiotelemetry device was sutured to the abdominal wall followed by closure of the peritoneal muscle and skin layers. Each transmitter device allowed for the simultaneous and continuous monitoring of 

\[ T_c \]

(°C·min) during heating (ascending) and cooling (descending) was calculated as intervals throughout experimentation and 24-h recovery period. Transmitters weighed \( \sim 11 \) g or \( \sim 4\% \) of presurgical body weight (BW). Rats were housed for 7 days upon arrival before the start of experimentation to acclimatize to the vivarium. Stable circadian 

\[ T_c \]

HR, and SBP rhythms were required in all rats prior to experimentation, indicating full surgical recovery and acclimatization to our vivarium. Each radiotelemetry device was calibrated prior to and following experimentation to ensure accurate measurements.

**Heating Protocol**

Rats in their original cages with bedding, food, and water were placed into a floor-standing incubator (Thermo Scientific, Asheville, NC) at an ambient temperature \( (T_a) \) of 20 ± 2°C for \( \sim 16 \) h acclimation to this novel environment prior to the initiation of heat exposure. Cage lid tops were removed to facilitate air circulation. Starting at \( -0.730 \) the following day, rats displaying a 

\[ T_c < 37°C \]

(12-h daytime average 

\[ T_c \]

of rats in this study) were weighed, food and water were removed from the cage, and the incubator 

\[ T_a \]

was increased to 37 ± 0.2°C. Heating continued until a predetermined experimental maximum 

\[ T_c (T_{c,\text{max}}) \]

of 41.9°C \( (n = 22) \) was attained. At 

\[ T_{c,\text{max}} \]

rats were removed from the incubator, weighed, placed in a new cage with access to food and water ad libitum, and maintained at a 

\[ T_a \]

of 20 ± 2°C in their original cage location until the time at which animals were euthanized. Control (CON) animals were exposed to the same experimental conditions at 

\[ T_a \]

of 20 ± 2°C with the timing of all procedures matched to that of a heated rat.

**Heating Calculations**

Time to 

\[ T_{c,\text{max}} \]

represents the total heat exposure time. Thermal strain (°C·min) during heating (ascending) and cooling (descending) were calculated as intervals × 0.5 (°C above 

\[ T_c = 40.0°C \]

at the start of the interval) and \( \Sigma \) of the time intervals × 0.5 (°C above 

\[ T_c = 40.0°C \]

at the end of the interval), respectively. Hypothermia was defined as a 

\[ T_c < 37.3°C \]

which was the lowest 

\[ T_c \]

value observed in undisturbed rats before heat stress (data not shown). Hypothermia depth (°C) was the lowest 1-min 

\[ T_c \]

value during recovery. Time to reach hypothermia depth was calculated as the time from 

\[ T_{c,\text{max}} \]

to the lowest 

\[ T_c \]

observed during recovery.

**Dehydration**

BW was measured on a top-loading balance with an accuracy of \( \pm 0.1 \) g. Percent dehydration was calculated as \( [(\text{preheat BW} - \text{postheat BW})/\text{preheat BW}] \times 100 \), which is an estimate that did not account for BW loss from feces or urine. Preheat BW was obtained immediately prior to heat exposure; postheat BW was obtained immediately upon removal from the heating chamber at 

\[ T_{c,\text{max}} \]

**(Blood Chemistry and Hematology)**

At 24 h of HS recovery, rats were rapidly (<1 min), deeply anesthetized with isoflurane (5% in 100% \( O_2 \); flow rate = 5 l/min). A thoracotomy was performed, and the rats were exsanguinated via cardiac puncture (5 ml syringe; 21-gauge needle). The blood was divided for immediate determination of biomarkers of cardiac damage (cardiac Troponin I; cTnI), renal function (blood urea nitrogen; BUN), and liver function/damage [glucose, albumin, and alanine aminotransferase (ALT)] via a handheld iSTAT clinical analyzer (Abbott Diagnostics, Abbott Park, IL) and VetScan VS2 modalities (Abaxis, Union City, CA).

**Histopathology**

Following cardiac puncture and exsanguination, the organs were perfused with cold heparinized (10 U/ml) 0.9% sterile saline. The heart, kidney, liver and brain were rapidly excised, sliced into transverse or longitudinal sections, and fixed in ExCell Plus (American MasterTech, Lodi, CA). Organs were embedded in paraffin blocks, and serial sections were stained with hematoxylin and eosin for microscopic evaluation at a magnification of \( \times 200 \) (IDEXX Laboratories, Grafton, MA). A certified veterinary pathologist determined the extent of organ damage. Histopathological findings were reported using a standard grading system \( (20) \) whereby 0 = no significant damage, 1 = minimal, 2 = mild, 3 = moderate, and 4 = severe damage. Heart and kidney tissues of 18 animals were analyzed, while 17 liver samples and 19 brain samples were analyzed.

**Statistics**

Data are presented as means ± SE. One-way ANOVA with Tukey’s post hoc test determined group effects. Significance was set at \( P < 0.05 \).

**RESULTS**

Based on 

\[ T_c \]

profiles observed during acute recovery, results were stratified into mild HS (MILD), moderate HS (MODERATE), and severe HS (SEVERE) groups. Following stratification, hemodynamic, histopathological and circulating biomarkers were compared among groups.

**Heat Exposure**

Thermoregulatory response during heat exposure. Table 1 outlines the thermal characteristics of heat exposure per severity of HS. No between-group differences existed in time to 

\[ T_{c,\text{max}} \]

or thermal strain during heat exposure (Table 1). CON rats maintained the normal daytime 

\[ T_c \]

of \( \sim 37°C \) during experimentation (data not shown).

**Hemodynamic adjustments during heat exposure**. Figure 1 illustrates HR and SBP responses during heat exposure per

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**Table 1. Characteristics of heat exposure**

<table>
<thead>
<tr>
<th>Heat Illness Severity</th>
<th>Nonheated Control (n = 10)</th>
<th>MILD (n = 11)</th>
<th>MODERATE (n = 6)</th>
<th>SEVERE (n = 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body weight loss, %</td>
<td>1.4 ± 0.9</td>
<td>8.0 ± 0.8*</td>
<td>7.4 ± 1.2*</td>
<td>10.4 ± 1.2*</td>
</tr>
</tbody>
</table>
| Time to 

\[ T_{c,\text{max}} \]

, min | N/A                       | 210.3 ± 76.5 | 192.5 ± 12.9    | 247.0 ± 67.2  |
| Ascending thermal area, °C·min       | N/A                       | 89.7 ± 10.1  | 93.0 ± 13.7     | 117.6 ± 15.0  |

Data are means ± SE. \( T_{c,\text{max}} \) maximal core temperature. *Nonheated control vs. all heated groups \( (P < 0.05) \).
severity of HS. The HR of heated animals began to significantly increase relative to CON values at ~60 min ($P < 0.02$) and remained elevated until time 0 ($T_{c,\text{Max}}$) (Fig. 1A). The HR of animals in the SEVERE group was significantly elevated relative to MILD at 30 min of heating (526 ± 5 vs. 464 ± 19, respectively; $P < 0.02$). At $T_{c,\text{Max}}$ HR of SEVERE and MODERATE animals were elevated above MILD (637 ± 13 and 596 ± 8 vs. 540 ± 14 beats/min, respectively; $P < 0.02$); however, no difference existed between SEVERE and MODERATE ($P < 0.11$; Fig. 1A).

The SBP of all heated animals was elevated over CON at 120 min and remained elevated throughout heating ($P < 0.001$; Fig. 1B). At 30 min the SBP of MODERATE animals was significantly elevated over MILD (215 ± 6 vs. 192 ± 7 mmHg, respectively; $P < 0.05$) but was not different from SEVERE (207 ± 7 mmHg; $P < 0.40$). Between 30 min and time 0 ($T_{c,\text{Max}}$), SEVERE and MODERATE animals incurred a

Fig. 2. Thermal profile during heat exposure through 24 h of recovery. Three distinct profiles are evident and correspond with MILD (A), MODERATE (B), and SEVERE (C) heat stroke (HS) severity. All rats show similar $T_c$ responses during heat exposure. MILD HS rats present with a monophasic response, MODERATE HS rats present with a biphasic response, and SEVERE HS rats present with a triphasic response during recovery. Group averages relative to CON rats demonstrate differences in the three response profiles (D). *CON vs. all heat stroke (HS) groups; †SEVERE vs. MILD; §SEVERE vs. MODERATE; ¶SEVERE vs. MILD and MODERATE. Significance set at $P < 0.05$.

Fig. 1. Heart rate (HR) and systolic blood pressure (SBP) responses during heat exposure per heat severity (A and B, respectively). HR is elevated above control (CON) rats in all heated groups at ~60 min, and SBP is elevated above CON at ~120 min; both patterns persist throughout heating. At maximum core temperature ($T_{c,\text{Max}}$) HR in animals with severe heat stroke (SEVERE) and moderate heat stroke (MODERATE) is significantly elevated relative to those with mild heat stroke (MILD). SBP is lower in SEVERE animals than MODERATE or MILD at $T_{c,\text{Max}}$, indicative of hemodynamic compromise. *CON vs. all heat stroke (HS) groups; †SEVERE vs. MILD; §SEVERE vs. MODERATE; ¶SEVERE vs. MILD and MODERATE. Significance set at $P < 0.05$. 

was significantly elevated over MILD (215 ± 6 vs. 192 ± 7 mmHg, respectively; $P < 0.05$) but was not different from SEVERE (207 ± 7 mmHg; $P < 0.40$). Between −30 min and time 0 ($T_{c,\text{Max}}$), SEVERE and MODERATE animals incurred a
drop in SBP (ΔSBP). The ΔSBP resulted in similar SBP for MODERATE and MILD animals (200 ± 3 vs. 201 ± 4 mmHg, respectively; \( P < 0.89 \)) at \( T_{c,\text{Max}} \). The ΔSBP was more substantial in SEVERE animals, resulting in a significantly lower SBP in those animals relative to MODERATE (178 ± 7 vs. 200 ± 3 mmHg, respectively; \( P < 0.05 \)) and a trend toward significance compared with MILD (201 ± 4 mmHg; \( P < 0.055 \); Fig. 1).

Recovery Profile

Thermal profile in acute recovery. The \( T_c \) profile of HS rats during 24 h of recovery is shown in Fig. 2. All CON rats showed virtually identical \( T_c \) rhythms with low daytime and high nighttime values observed during the lights-on and lights-off period, respectively (grouped for ease of presentation; Fig. 2). Starting at \( T_{c,\text{Max}} \) (time 0), rats showed interindividual variability in their \( T_c \) recovery responses through 24 h, with three distinct profiles correlating with HS severity. Eleven (50%) animals displayed a monophasic profile during recovery that was characterized by rapid cooling to 38.5 ± 0.2°C, which was sustained throughout recovery and remained significantly elevated above CON rats (37.5 ± 0.1°C; \( P < 0.001 \); Fig. 2A). All monophasic rats survived through 24 h of recovery. Five (25%) rats displayed a biphasic recovery profile characterized by rapid cooling and a return to baseline \( T_c \) followed by rebound hyperthermia that was maintained throughout the remainder of the recovery period (Fig. 2B). The average \( T_c \) of biphasic animals following the rebound through 24 h of recovery was 38.5 ± 0.2°C, which was higher than CON values (\( P < 0.001 \)), but was not different from the monophasic response. Three (14%) animals displayed a triphasic profile characterized by rapid cooling with a return to baseline \( T_c \) and a subsequent rebound that was similar in profile to the biphasic response. The hyperthermic rebound was followed by a hypothermic phase characterized by hypothermia depth of ~35°C (Fig. 2C). Figure 2D shows the average \( T_c \) profile of the three HS groups through 24 h of recovery, and Table 2 describes the timeline of \( T_c \) responses and acute recovery characteristics of each group. One (5%) postheat thermal dataset was unrecoverable, two (9%) rats (1 biphasic, 1 triphasic) succumbed during HS recovery, and the remaining 20 (91%) heated and all CON rats survived to study end point (Table 2).

All thermal profiles during acute recovery correlated with HR and SBP responses during heat exposure such that all animals displaying significant hemodynamic compromise during heat had a triphasic profile in recovery and therefore maintained characterization as Severe. All animals displaying strained hemodynamic challenge during heat exposure exhibited rebound hyperthermia on acute recovery and thus remained characterized as MODERATE severity. Likewise, animals displaying mild hemodynamic compensation during heat exposure exhibited a monophasic thermal profile on acute recovery and thus maintained classification as MILD.

Biomarkers of tissue damage at 24 h of recovery. Table 3 shows circulating biomarkers of organ damage for CON, MILD, MODERATE, and SEVERE HS rats at 24 h of recovery. MODERATE was associated with significant increases in circulating levels of cTNI, BUN, glucose, or ALT at 24 h of recovery, whereas albumin levels were significantly lower in this group compared with CON (Table 3). MODERATE was associated with significant increases in circulating cTNI and ALT, and decreased glucose and albumin compared with CON rats (\( P < 0.05 \); Table 3). SEVERE rats showed significant alterations in all biomarkers with cTNI, BUN, and ALT elevated and glucose decreased. MODERATE severity resulted in a significant increase in circulating cTNI compared with CON (\( P < 0.05 \)). BUN and glucose showed a similar trend, but failed to reach statistical significance (\( P = 0.053 \) and \( P = 0.059 \), respectively; Table 3).

Table 3. Circulating biomarkers of organ damage at 24 h of HS recovery

<table>
<thead>
<tr>
<th></th>
<th>Nonheated Control (n = 10)</th>
<th>MILD (n = 11)</th>
<th>MODERATE (n = 5)</th>
<th>SEVERE (n = 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cTNI, ng/ml</td>
<td>1.3 ± 0.4</td>
<td>3.2 ± 1.3</td>
<td>13.9 ± 2.1†</td>
<td>39.1 ± 5.6*§</td>
</tr>
<tr>
<td>BUN, mg/dl</td>
<td>17.2 ± 0.7</td>
<td>17.3 ± 1.2</td>
<td>26.4 ± 5.7</td>
<td>33.5 ± 2.7†</td>
</tr>
<tr>
<td>Glucose, mg/dl</td>
<td>193.3 ± 5.3</td>
<td>190.3 ± 7.8</td>
<td>155.0 ± 7.8*†</td>
<td>161.0 ± 5.1*†</td>
</tr>
<tr>
<td>Albumin, g/dl</td>
<td>4.6 ± 0.1</td>
<td>4.1 ± 0.1*†</td>
<td>3.5 ± 0.1*†</td>
<td>3.6 ± 0.1*†</td>
</tr>
<tr>
<td>ALT, U/l</td>
<td>76.0 ± 2.3</td>
<td>535.2 ± 228.2</td>
<td>1,848 ± 369.2*†</td>
<td>1,213.8 ± 474.4*</td>
</tr>
</tbody>
</table>

Date are means ± SE. Significance set at \( P < 0.05 \): *vs. Control; †vs. MILD; §vs. MODERATE. cTNI, cardiac troponin I; BUN, blood urea nitrogen; ALT, alanine aminotransferase; HS, heat stroke.
Histopathological analysis of organ damage at 24 h of recovery. Table 4 outlines the histopathological findings per organ per HS severity. At 24 h of recovery, 12 (67%) of the animals displayed moderate myocardial damage. Renal damage was concentrated in the mild to moderate grades with nine (50%) animals falling into these categories; six (33%) displayed severe damage. Liver damage was distributed equally between minimal (n = 4, 24%), moderate (n = 4, 24%), and severe (n = 3, 18%) gradients; however, six (35%) animals showed no liver damage. The majority of rats showing no liver damage were of MILD HS severity, whereas all animals with severe liver damage were SEVERE HS animals. However, it was not possible to definitively determine HS severity based on histopathology alone presumably due to the small sample size within each standard grading category.

Representative micrographs from one CON and one SEVERE rat are presented in Fig. 3. No significant abnormalities were detected in CON rats (Fig. 3, A, C, and E). The heart of the SEVERE rat shows myocardial necrosis and myofiber degeneration consistent with late-stage ischemic cardiomyopathy and infarction (Fig. 3B). Acute tubular necrosis and hyaline droplet degeneration in the kidney was consistent with kidney nephrosis (Fig. 3D), and acute, multifocal necrosis of the liver (Fig. 3F).

DISCUSSION

The major findings of our present study are threefold. First, we identified specific temporal patterns of Tc responses that distinguished between MILD, MODERATE, and SEVERE pathophysiology in this novel, freely moving rat model of HS that differ significantly from the thermoregulatory patterns observed in mice. Second, we identified HR and SBP patterns during heat exposure that were closely linked to HS severity. Third, we identified associations between hemodynamic alterations during heat exposure, Tc in acute recovery, high circulating cTnI levels, and histopathological changes in the heart at 24 h of recovery. These major findings are consistent with existing clinical information about HS responses in humans.

Table 4. Histopathological analysis of organ damage at 24 h of recovery

<table>
<thead>
<tr>
<th>Organ</th>
<th>Standard Grading Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td><strong>Heart</strong></td>
<td></td>
</tr>
<tr>
<td>Nonheated control, % (n)</td>
<td>100 (10)</td>
</tr>
<tr>
<td>MILD, % (n)</td>
<td>22 (2)</td>
</tr>
<tr>
<td>MODERATE, % (n)</td>
<td>60 (3)</td>
</tr>
<tr>
<td>SEVERE, % (n)</td>
<td>25 (1)</td>
</tr>
<tr>
<td><strong>Kidney</strong></td>
<td></td>
</tr>
<tr>
<td>Nonheated control, % (n)</td>
<td>100 (10)</td>
</tr>
<tr>
<td>MILD, % (n)</td>
<td>33 (3)</td>
</tr>
<tr>
<td>MODERATE, % (n)</td>
<td>44 (4)</td>
</tr>
<tr>
<td>SEVERE, % (n)</td>
<td>60 (3)</td>
</tr>
<tr>
<td><strong>Liver</strong></td>
<td></td>
</tr>
<tr>
<td>Nonheated control, % (n)</td>
<td>100 (10)</td>
</tr>
<tr>
<td>MILD, % (n)</td>
<td>56 (5)</td>
</tr>
<tr>
<td>MODERATE, % (n)</td>
<td>25 (1)</td>
</tr>
<tr>
<td>SEVERE, % (n)</td>
<td>25 (1)</td>
</tr>
</tbody>
</table>

Histopathological findings were reported using a standard grading system whereby 0 = no significant damage, 1 = minimal damage, 2 = mild damage, 3 = moderate damage, and 4 = severe damage. The major findings of our present study are threefold. First, we identified specific temporal patterns of Tc responses that distinguished between MILD, MODERATE, and SEVERE pathophysiology in this novel, freely moving rat model of HS that differ significantly from the thermoregulatory patterns observed in mice. Second, we identified HR and SBP patterns during heat exposure that were closely linked to HS severity. Third, we identified associations between hemodynamic alterations during heat exposure, Tc in acute recovery, high circulating cTnI levels, and histopathological changes in the heart at 24 h of recovery. These major findings are consistent with existing clinical information about HS responses in humans.
physiology (12, 38). However, the cardiosuppressant and sympathoinhibitory effects of anesthesia complicate interpretation of cardiovascular findings (10, 32). Furthermore, anesthetic agents generally exert a prophylactic, preconditioning-like effect on the myocardium (39). Second, existing studies in both conscious and anesthetized rats have used changes in arterial pressure to identify HS onset (1, 7, 21, 31, 38). In this context, the use of blood pressure data to define the onset of heat stroke varies widely among studies. Our present data suggest that HR is more strongly correlated with HS severity than arterial pressure. Third, many studies have used a predefined $T_{c, \text{Max}}$ to define HS onset (22, 23, 33, 35); however, our present data suggest that interindividual variability in responsiveness precludes the use of a predetermined $T_{c, \text{Max}}$ as the major indicator of HS severity. Our conscious rat HS model overcomes these experimental limitations and provides novel insight into the predictive value of cardiovascular, thermoregulatory and circulating biomarkers through 24 h of recovery.

A catastrophic consequence of HS is multiorgan failure, which is considered the underlying etiology of mortality. In the present study, high cTnI levels and damage to the heart substantiated the predictive value of the $T_c$ and hemodynamic responses observed. cTnI was elevated nearly 40-fold at 24 h of recovery in SEVERE rats, whereas this biomarker generally peaks at 6–18 h (3, 11, 18) in patients experiencing myocardial injury. cTnI is not currently included in traditional clinical heat panels, which routinely consist of a complete blood count, metabolic profile, and markers of kidney and liver damage/dysfunction (6, 25). We propose that cTnI is a sensitive biomarker that could improve assessment and treatment of cardiac damage during HS recovery. It will be important in future studies to determine cTnI levels at several time points during recovery to identify the time course of changes and the predictive power of this biomarker throughout recovery. Interestingly, there was a strong correlation between circulating cTnI and BUN levels (at 24 h of recovery), suggesting acute dysfunction of the heart may have contributed to renal dysfunction. Dehydration and ischemia are known to induce kidney dysfunction with HS, but impaired cardiac function may be an additional factor that has not been previously considered.

MODERATE and SEVERE rats displayed ~20% reduction in blood glucose levels at 24 h of recovery. Hypoglycemia has
been observed in case reports and other experimental HS models (4, 15). However, we showed in a mouse HS model that glucose normalized to control levels within 24 h (15), whereas in the present study MODERATE and SEVERE rats remained hypoglycemic at this time point. A probable cause for the discrepancy between studies was the lack of liver damage in HS mice through 24 h of recovery (15). Consistent with this hypothesis, the liver of MILD rats was, at most, minimally damaged whereas the majority of MODERATE and SEVERE rats suffered substantial liver damage (Table 4). As such, thermal or ischemic injury to the liver in the current study may have compromised glucose homeostasis.

In summary, we have developed a conscious, freely moving rat model of HS in which we have identified Tc, cardiovascular, and circulating biomarkers of HS severity and organ damage. We propose that robust HR and SBP responses observed during heat exposure are more sensitive biomarkers of HS severity than core temperature or thermal strain. Finally, our data suggest that cTnI in combination with traditional clinical biomarkers of organ damage may improve diagnosis and treatment of organ damage during the early stages of HS recovery.

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GRANTS

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS


REFERENCES


