Preischemic Hyperglycemia Leads to Delayed Postischemic Hyperthermia

Hiroyuki Uchino, MD; Johan Lundgren, MD, PhD; Maj-Lis Smith, PhD; Bo K. Siesjö, MD, PhD

Background and Purpose  Temperature alterations are known to influence the outcome of transient ischemia, even when instituted in the postischemic period. Since preischemic hyperglycemia aggravates ischemic brain damage, the question of whether hyperglycemic animals become hyperthermic arose. To explore this possibility, we measured body temperature telemetrically in normoglycemic and hyperglycemic rats subjected to 10 minutes of forebrain ischemia at a body (and brain) temperature of 37°C.

Methods  Isoflurane-anesthetized animals were subjected to 10 minutes of forebrain ischemia under normoglycemic or hyperglycemic conditions. Temperature changes after ischemia were measured by means of a telemetric temperature coil.

Results  In normoglycemic animals, temperature decreased to 35.6±1.1°C (mean±SD) during the first 4 hours of recovery, after which it gradually increased to normal values (38°C). Hyperglycemic animals behaved differently in that they remained normothermic for approximately 10 hours during recovery and later became hyperthermic, with core temperatures rising above 39°C. The rise in temperature was not due to the osmotic load of the glucose administered because infusion of mannitol, which gave a comparable increase in plasma osmolality, failed to cause delayed postischemic hyperthermia. Excessive hypercapnia during ischemia in normoglycemic animals, which produces cerebral acidosis of a magnitude similar to that of hyperglycemia and is known to aggravate ischemic lesions, likewise failed to induce hyperthermia. When postischemic seizures ensued in hyperglycemic subjects, temperature was 39.8±0.6°C. Animals with seizures invariably died. To evaluate the influence of postischemic hyperthermia on the outcome, an additional series of experiments was performed in which delayed hyperthermia was avoided by gentle cooling (n=6) or by acetaminophen administration (n=5). Although these procedures prevented delayed hyperthermia, they neither blocked seizure induction nor affected the fatal outcome. Postischemic seizures developed when the core temperatures of animals were 37.9±0.1°C and 37.8±0.2°C in the cooled and acetaminophen-treated groups, respectively.

Conclusions  The results suggest that both delayed hyperthermia and delayed seizures in hyperglycemic animals are caused by the aggravated damage incurred by these animals during or immediately after the ischemic insult. (Stroke. 1994;25:1825-1829.)

Key Words  •  cerebral ischemia  •  hyperglycemia  •  seizures  •  temperature  •  rats

Transient ischemia leads to brain damage of two types. In the first, cellular necrosis affects neurons in selectively vulnerable areas.1-3 In the second type, damage affects all cell populations, yielding pan necrosis or infarction.4 Preischemic hyperglycemia aggravates damage due to dense, transient ischemia in adult animals.5-10 Cardinal features of hyperglycemia-augmented damage are the conversion of selective neuronal necrosis into infarction,9-12 the rapid evolution of brain damage, the involvement of additional structures, such as the cingulate cortex and substantia nigra pars reticulata, and the development of postischemic seizures.5,6,10,13-15 The worsening of outcome is assumed to be related to accumulation of lactate plus H+ produced by the increased amount of available glucose.16 Another factor that aggravates brain damage due to transient ischemia is hyperthermia, which, like hyperglycemia, transforms selective neuronal vulnerability into infarction.17,18 The mechanisms are not necessarily identical, however; for example, hyperthermia has not been reported to trigger postischemic seizures.17,20

These results raise the question of whether hyperglycemic animals develop postischemic hyperthermia and whether such hyperthermia could explain the appearance of seizures and the aggravation of damage. To shed light on this problem, we recorded core temperature telemetrically in normoglycemic and hyperglycemic animals subjected to transient ischemia. Additional series were studied to assess the effect of an increase in plasma osmolality and of enhanced tissue acidosis in the absence of hyperglycemia. When the result revealed that only hyperglycemic animals developed delayed hyperthermia, experiments were performed in which the hyperthermic response was prevented by environmental cooling or administration of acetaminophen, and seizure incidence was recorded in these temperature-regulated animals.

Materials and Methods

The experiments were performed on adult male Wistar rats (weight, 290 to 370 g) of a specific-pathogen-free strain (Mallegaard's Breeding Center, Copenhagen, Denmark). The animals were housed in macrolon cages and exposed to a 12-hour day and night cycle and a room temperature of 22°C.
by the Ethical Committee for Laboratory Animal Experiments at the University of Lund.

Statistical evaluation of physiological variables was performed with ANOVA followed by Dunnett's test, and the time course of temperature changes among groups was statistically assessed with two-factor ANOVA followed by Scheffé's tests. A value of \( P < 0.05 \) was considered statistically significant.

### Results

#### Physiological Parameters

No statistical differences were observed in blood pressure, temperature, \( \text{PaO}_2 \), \( \text{PaCO}_2 \), and \( \text{pH} \) between the normoglycemic and hyperglycemic groups or between any of the hyperglycemic groups before, during, or after ischemia until 20 to 40 minutes of recovery. Skull and rectal temperatures were kept at 37°C throughout the steady-state period as well as during ischemia and the early recirculation phase (20 minutes).

### Core Temperature After Transient Brain Ischemia in Normoglycemic and Hyperglycemic Rats

The results of this series are given in Fig 1. In the normoglycemic group \((n=9)\), the temperature during the first 4 hours gradually decreased to a mean value of 35.6°C and thereafter slowly increased to and remained at approximately 38°C, the temperature of a normal awake rat (Fig 1A). Some variability was evident, since two rats showed hyperthermia (>39.0°C) after 15 hours of recovery. One of these developed seizures after 17.5 hours of recovery and died.

The hyperglycemic rats (Fig 1B) showed a different pattern. They remained normothermic during the early phase of recovery, but temperature increased spontaneously after approximately 10 hours of recirculation, to mean values exceeding 39°C (Fig 1B). Six of 17 hyperglycemic rats developed early postischemic seizures, and 5 of 6 died in close relation to these seizures (between 3 and 6 hours of recovery). The 6 rats that developed early seizures did not differ in temperature from the 11 animals that did not develop early postischemic seizures (Fig 1B). When the 5 rats that succumbed early were excluded, the hyperglycemic animals showed generalized convulsions at a mean recovery time of 18.2±1.7 hours and subsequently died (20.2±3.4 hours of recovery). The temperature of the dying animals fell, as seen in Fig 1B. The mean temperature when the first seizure was observed was 39.8±0.6°C. Interestingly, animals consis-
A Hypercapnic ischemia  

B Hyperosmotic ischemia

Fig 2. Line graphs show postischemic core temperature (Temp) in rats with induced hypercapnia (A) or hyperosmolarity (B). Hypercapnic rats were ventilated with 50% CO₂ for 10 minutes before and during ischemia. Hyperosmotic rats were infused with 15% mannitol before ischemia to increase the plasma osmolality. Values are mean±SD.

Fig 3. Line graphs show core temperature (Temp) during 24 hours of recovery after 10 minutes of transient ischemia in hyperglycemic rats cooled with cold air (A) and hyperglycemic rats given acetaminophen (B). Arrows indicate initiation of gentle cooling (A) and first time point of acetaminophen administration (75 mg·kg⁻¹) (B). Values are mean±SD.

tently showed a drop in core temperature immediately after each seizure episode. The time course of the temperature changes in hyperglycemic rats showed a significant difference from those in normoglycemic, hypercapnic, or hyperosmotic rats (P<.01). No significant difference was obtained among rats subjected to normoglycemic, hypercapnic, and hyperosmotic ischemia.

Hypercapnic and Mannitol-Infused Rats

To study whether the rise in temperature of hyperglycemic animals was related to the exaggeration of intracellular and extracellular acidosis, such exaggeration was reproduced by superimposed hypercapnia. As Fig 2A shows, hypercapnic animals remained moderately hypothermic for 16 to 20 hours and never developed hyperthermia. In agreement with data reported by Katsura et al, we found that hypercapnic animals did not develop postischemic seizures (observation period, 24 hours of recovery).

The results were similar in animals infused with mannitol to increase their plasma osmolality (Fig 2B). Thus, hyperosmolality per se cannot be held responsible for delayed hyperthermia.

Effect of Suppression of Hyperthermia

In the second series of animals, we attempted to counteract the temperature increase in the hyperglycemic animals by cooling the ambient air by packing ice around the cage or by oral administration of acetaminophen. Fig 3 illustrates that both air cooling and acetaminophen could completely suppress delayed hyperthermia. After 12 hours of recovery and thereafter, animals in the cooled or acetaminophen-treated groups showed significantly lower core temperatures than the untreated hyperglycemic groups. No rats showed early seizures.

Although hyperthermia could be avoided, the time point for the development of late postischemic seizures did not change, since seizures occurred after 19.3±3.3 hours in the cooled group and after 20.0±1.8 hours in the acetaminophen-treated group, starting when the animals showed a core temperature of 37.9±0.1°C and 37.8±0.2°C, respectively. In addition, although 3 of 11 cooled animals survived until 2 to 4 days of recovery, most animals died after 20 to 25 hours, and none survived for more than 4 days.

Discussion

The results of the present study demonstrate that animals rendered hyperglycemic before a transient ischemic insult develop a delayed increase in body temperature, which becomes manifest after approximately 10 hours of recirculation. This rise in temperature thus precedes the appearance of late postischemic seizures, which are observed after 18 to 26 hours of recovery.

However, the tendency for hyperglycemic animals to develop hyperthermia is evident already during the first 6 to 8 hours of recovery. Thus, whereas normoglycemic rats demonstrate a transient decrease in body temperature during the early recirculation hours, hyperglycemic rats maintain body temperature 1.0°C to 2.0°C higher in that period. We will discuss the mechanisms involved in this difference in temperature response and the pathophysiological effects of the immediate and delayed rises in body temperature. This discussion is facilitated by our results in hypercapnic and mannitol-infused animals since they show that neither aggravation of tissue acidosis alone nor hyperosmolality can be held responsible for the hyperthermia.

Body temperature is controlled by thermoregulatory centers in the brain, mainly localized in the anterior (preoptic area) and posterior hypothalamus. Lesions
in the anterior hypothalamus are known to cause hyperthermia. Such lesions may explain why middle cerebral artery occlusion by an intraluminal filament frequently leads to hyperthermia. However, although middle cerebral artery occlusion by this technique may lead to hypothalamic lesions, ischemia. In hyperglycemic subjects is not known to cause such lesions. It would thus seem that more subtle alterations in the function of temperature-regulating centers are responsible for the hyperthermic effect. However, by reexamining histological material from a previous study, we found discrete lesions in hypothalamic nuclei in 15 of 36 animals with preischemic hyperglycemia.

Postischemic hyperthermia has previously been described in gerbils and in the absence of deliberately raised environmental temperature. In this species, temperatures increase to 38.5°C to 39°C within the first 2 to 3 hours of recovery. This early hyperthermia has been found to be associated with an aggravation of brain damage. However, in the present experiments on rats, normoglycemic animals showed a postischemic decrease in body temperature to minimal values of 35.5°C, although they were freely moving in an environment of normal temperature (22°C) and humidity. In contrast, hyperglycemic animals showed a rise in temperature toward 36.0°C, the normal body temperature of awake rats.
Intraischemic and postischemic hyperthermia have been shown in several ischemia models to aggravate brain injury.\textsuperscript{1-3} In adult animals, preischemic hyperglycemia also exacerbates ischemic damage.\textsuperscript{4-5} The results reported by Uchino and colleagues nicely demonstrate that hyperglycemic animals develop a delayed increase in body temperature after 10 hours of recirculation. Thus, the question of whether this delayed hyperthermic response is a cause or consequence of hyperglycemic tissue damage and seizure activity was investigated.

The present data indicate that in hyperglycemic rats in which delayed hyperthermia was avoided, seizure induction and fatal outcome were not prevented. Thus, early structural damage to thermoregulatory brain regions may have caused the late temperature elevations. Since preischemic hyperglycemia aggravates the early neuronal and microvascular consequences of ischemia,\textsuperscript{6,7} early tissue injury may lead to the generation and release of factors that could also affect body temperature.

The use of continuous telemetric monitoring of the core temperature provided new information regarding the natural response of body temperature to cerebral ischemic damage. In previous studies, spontaneous hyperthermic periods had been documented after middle cerebral artery occlusion in rats\textsuperscript{3} and after bilateral common carotid artery occlusion in gerbils.\textsuperscript{8} Based on the present findings, one might question whether the temporal response or the magnitude of the hyperthermic periods is similar between body and brain.

W. Dalton Dietrich, PhD,
Department of Neurology
University of Miami
School of Medicine
Miami, Fla

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H Uchino, J Lundgren, M L Smith and B K Siesjö

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