

Research Article

5'-Adenosine Monophosphate-Induced Hypothermia Attenuates Brain Ischemia/Reperfusion Injury in a Rat Model by Inhibiting the Inflammatory Response

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Hypothermia treatment is a promising therapeutic strategy for brain injury. We previously demonstrated that 5'-adenosine monophosphate (5'-AMP), a ribonucleic acid nucleotide, produces reversible deep hypothermia in rats when the ambient temperature is appropriately controlled. Thus, we hypothesized that 5'-AMP-induced hypothermia (AIH) may attenuate brain ischemia/reperfusion injury. Transient cerebral ischemia was induced by using the middle cerebral artery occlusion (MCAO) model in rats. Rats that underwent AIH treatment exhibited a significant reduction in neutrophil elastase infiltration into neuronal cells and matrix metalloproteinase 9 (MMP-9), interleukin-1 receptor (IL-1R), tumor necrosis factor receptor (TNFR), and Toll-like receptor (TLR) protein expression in the infarcted area compared to euthermic controls. AIH treatment also decreased the number of terminal deoxynucleotidyl transferase dUTP nick end labeling- (TUNEL-) positive neuronal cells. The overall infarct volume was significantly smaller in AIH-treated rats, and neurological function was improved. By contrast, rats with ischemic brain injury that were administered 5'-AMP without inducing hypothermia had ischemia/reperfusion injuries similar to those in euthermic controls. Thus, the neuroprotective effects of AIH were primarily related to hypothermia.

1. Introduction

Stroke is the leading cause of severe, long-term disability worldwide [1]. A number of chemical agents have been shown to have neuroprotective effects following ischemic brain injury in the laboratory, only to fail in the clinic [2], indicating a need for novel therapeutic strategies. An active and important area of cerebrovascular research is therapeutic hypothermia after stroke. Mild or deep hypothermia has yielded beneficial results in animal models of brain ischemic injury [3, 4]. Artificially lowering body and brain temperatures can significantly reduce the deleterious effects of several forms of brain injury, including traumatic brain injury [5], stroke [6], and neonatal hypoxic-ischemic encephalopathy [7].

However, despite widespread recognition of the beneficial effects of hypothermia, acceptance of this method of treatment within the medical community is limited. In the United States, only 2% of eligible patients receive this treatment option [8]. There are several reasons why this form of treatment remains underutilized. One major factor limiting the medical use of hypothermia is the technical difficulty of cooling a patient [9]. In this study, we sought to determine whether 5'-AMP-induced hypothermia (AIH) can overcome this obstacle and facilitate the use of therapeutic hypothermia.

5'-Adenosine monophosphate (5'-AMP), also known as 5'-adenylic acid, is a nucleotide that is found in DNA. 5'-AMP is an ester of phosphoric acid and the nucleoside adenosine.

We previously reported [10] a novel method for using 5'-AMP to facilitate the induction of a hypometabolic state in mice following a rapid lowering of body temperature. When we maintained the ambient temperature (T_a) at approximately 15°C, the animal's core body temperature (T_b) could be safely reduced to 16–17°C. This hypothermic state is linked to hypometabolism and a low affinity of erythrocytes for oxygen. Mice subjected to this treatment remained in this deep hypothermic state for several hours if the ambient temperature was maintained at approximately 15°C. During the hypothermic period, T_b can be maintained without encountering a severe thermoregulatory defense. When T_a is increased to normal room temperature, T_b also increases to normal body temperature. However, if T_a is normal during treatment with 5'-AMP, 5'-AMP does not induce deep hypothermia. These characteristics of 5'-AMP offer a practical way to control core body temperature. Additional experiments demonstrated that AIH treatment also has a cardioprotective effect after myocardial infarction in mice.

Thus, in the present study, we sought to determine the dose of 5'-AMP capable of inducing stable and deep hypothermia in rats. We then investigated whether such deep hypothermia induced by 5'-AMP reduces brain infarct size, inflammation, and neuronal apoptosis and improves neurological function in a brain ischemia/reperfusion model in rats.

2. Materials and Methods

2.1. Animals and Experimental Groups. Adult male Sprague-Dawley (SD) rats weighing 270–300 g were housed under diurnal lighting conditions (12 h light/dark). Experiments were performed in accordance with international guidelines for animal research. All experiments were approved by the Ethics Committee of the Animal Care and Experimental Committee of the School of Medicine of Shanghai Jiao Tong University, Shanghai, China.

For the dose study, rats were randomly assigned to four groups: (1) vehicle (Veh, $n = 9$); (2) low dose (AMP(0.25), $n = 9$): 0.25 mg 5'-AMP/g body weight was injected intraperitoneally (IP); (3) median dose (AMP(0.5), $n = 9$): 0.5 mg 5'-AMP/g body weight was injected IP; and (4) high dose (AMP(1.0), $n = 9$): 1.0 mg 5'-AMP/g body weight was injected IP. For the neuroprotection study, animals were randomly assigned to four groups: (1) sham (sham, $n = 18$): rats underwent the same surgical procedure without ischemia; (2) focal ischemia/reperfusion + normothermia (MCAO, $n = 22$): T_b in rats in this control group was approximately 37°C; (3) normothermia + 5'-AMP (NT, $n = 22$): at the end of ischemia, 5'-AMP was administered IP, but the T_b of the rats was kept euthermic by maintaining T_a at 33–34°C for 6 h; (4) hypothermia + 1.0 mg 5'-AMP/g body weight (HT(1.0), $n = 20$): 1.0 mg 5'-AMP/g body weight was administered at the end of ischemia/reperfusion, and the rats were kept at T_a of 15°C; after 6 h at 15°C, all AIH-treated rats were returned to normal care; and (5) hypothermia + 0.5 mg 5'-AMP/g body weight (HT(0.5), $n = 20$): all procedures were similar to those for the HT(1.0) group, except that the 5'-AMP dose was 0.5 mg/g body weight.

2.2. Induction of Deep Hypothermia by 5'-AMP. 5'-AMP was purchased from Sigma (St. Louis, MO, USA). Anesthesia was induced by inhalation of 5% isoflurane and maintained with 2% isoflurane during surgery and the early stages of reperfusion. A freshly prepared solution of 5'-AMP in phosphate-buffered saline (PBS) was injected IP. During the experiments, T_b was monitored using a digital thermometer (T&W Industry Co., Ltd., China) with the probe placed approximately 1 cm into the anus. A six-needle electrocardiogram (ECG) and consecutive measurements of femoral artery blood pressure were recorded for all rats. The tail artery was cannulated to measure physiological parameters (pH, pCO₂, and pO₂) using a blood gas analyzer (International Technidyne Co., USA).

2.3. Transient Cerebral Ischemia/Reperfusion Protocol. Transient cerebral ischemia was induced in rats by middle cerebral artery occlusion (MCAO) as described previously [11]. After anesthesia a midline neck incision was made to expose the left common carotid artery. The external carotid artery was ligated using a bipolar coagulator. A nylon filament (diameter 0.24–0.28 mm) was gently inserted into the left internal carotid artery until resistance was felt. Cerebral blood flow then dropped sharply, indicating that the ischemia model was successfully established. Reperfusion was induced by removing the filament after 90 min of ischemia. Sham-operated animals were subjected to the same anesthesia, incision, and exposure of the vessels but without blood occlusion. Before the AMP treatment, the body temperature was monitored and maintained at $37.5 \pm 0.5^\circ\text{C}$ with a rectal thermistor and a heat lamp.

2.4. CBF Measurements. A laser Doppler flow meter (PeriFlux System 5000, Perimed, Sweden) was applied to detect CBF throughout the experiments and was connected to a standard laser Doppler monitor (PeriFlux 5000 LDPM unit and PF5000 main unit, Perimed, Sweden). The holder for the Doppler probe was attached on the left side of the skull in the ischemic penumbra region, 2 mm lateral and 2 mm posterior to bregma. The CBF recorded prior to occlusion was regarded as the baseline value. All CBF values were expressed as percentages of the baseline value.

2.5. Neurological Behavioral Assessment. The rotarod treadmill (AccuScan, Inc., Columbus, OH, USA) test was used to test motor function 1 day after the surgery and treatment. Each animal was placed in a neutral position on a cylindrical rod (3 cm diameter for rats), and the rod was then rotated with the speed accelerating linearly from 0 to 24 rpm within 60 s; the time spent on the rotarod was recorded automatically. The maximum score given to an animal was set to 60. The average score for the three trials was recorded for 9 animals in each group.

2.6. Infarct Volume Measurement. Animals were euthanized with CO₂ following neurological assessment. The brains were frozen for 3 minutes in -20°C refrigerator and divided into six 2 mm thick coronal sections. Tissue sections were then immediately stained with 2% 2,3,5-triphenyl tetrazolium

chloride (TTC) in PBS at 37°C for 20 min. Stained sections were imaged using a digital camera (Nikon E5100) and quantified using ImageJ software (version 1.37c, NIH). The infarct volume was computed as the sum of the measured infarct areas of the evenly sliced (2 mm) brain sections (Simpson's rule).

2.7. In Situ Labeling of DNA Fragmentation Using TUNEL Staining. Twenty-four hours after surgery, the rats were euthanized with CO₂ and perfused transcardially with cold PBS. TUNEL staining of tissue sections was used to assess apoptosis in the infarcted area in accordance with the manufacturer's protocol (Roche Diagnostics GmbH, Mannheim, Germany) for 9 animals in each group. Briefly, the sections were washed with PBS at room temperature for 30 min and permeabilized with 0.1% Triton X-100 in 0.1% sodium citrate solution at 4°C for 2 min. Approximately 50 µL of the TUNEL reaction mixture solution was incubated with each slide at 37°C for 1 h. All sections were overlaid with ProLong mounting reagent with DAPI (Invitrogen, Oregon, USA) and covered with coverslips. A Nikon ECLIPSE Ti fluorescence microscope and a CoolSNAP photometric camera were used to detect and acquire the images. TUNEL-positive cells (bright green fluorescence) were quantified using NIS-Elements BR diagnostic software, version 3.2.

2.8. Immunofluorescence Staining. Brain sections (10 mm) were incubated with 10% normal goat serum/0.1% Triton-X 100 in PBS (blocking solution) at room temperature for 1 h for 9 animals in each group. Anti-neutrophil elastase (1:200, Epitomics, Burlingame, CA, USA, Cat No. ab21595) and anti-NeuN (1:500, Millipore, MA, USA, Cat No. MAB377) primary antibodies were added to the slides, and the slides were incubated overnight at 4°C. After incubation, the slides were washed and then were incubated for 1 h with a secondary antibody: Alexa Fluor 488 goat anti-rabbit IgG (1:300, Invitrogen, Carlsbad, CA, USA, Cat No. A-24922) or Alex Fluor 568 goat anti-mouse IgG (1:500, Invitrogen, Carlsbad, CA, USA, Cat No. A-11031). DAPI was used to stain the nuclei in the tissue sections. All fluorescence results were obtained using a Nikon ECLIPSE Ti fluorescence microscope (400× magnification) coupled to a CoolSNAP photometric camera.

2.9. Western Blot Analysis. The levels of inflammation-related proteins were detected by western blot analysis 24 h after reperfusion for 9 animals in each group. Protein extraction reagents were used to extract total protein. Approximately 50 µg of protein was separated by electrophoresis in an 11.5% sodium dodecylsulfate-polyacrylamide gel. Polypeptides were transferred onto an Immobilon PVDF membrane (Millipore) by electrophoretic transfer at 300 mA for 1 h on ice. The membranes were then blocked with 5% nonfat milk in TBS-Tween (TBST). After blocking, the membranes were rinsed and then incubated overnight with the following antibodies: matrix metalloproteinase 9 (MMP-9) (1:200, Cell Signaling, Woburn, MA, USA, Cat No. 3852), interleukin-1 receptor (IL-1R) (1:200, Cell Signaling, Woburn, MA, USA, Cat No. 3865), tumor necrosis factor receptor (TNFR)

(1:500, Epitomics, Burlingame, CA, USA, Cat No. 11119), Toll-like receptor (TLR) (1:600, Cell Signaling, Woburn, MA, USA, Cat No. 12276), or β-actin (1:1000, Sigma-Aldrich, St. Louis, MO, USA). The membranes were then washed with TBS and incubated with horseradish peroxidase-conjugated secondary antibodies (1:800, Santa Cruz Inc., USA) in 1% nonfat milk in TBST for 2 h at room temperature. The results were visualized using the ChemiDoc XRS Imaging System (Bio-Rad Laboratories, Hercules, CA, USA), and the band densities were quantified using the MultiGauge Software of Science Lab 2006 (Fujifilm Corporation, Tokyo, Japan). Six animals were analyzed for each group for the western blot analysis.

2.10. Statistical Analysis. All data are expressed as the mean ± SEM. The neurological scores were analyzed using the Mann-Whitney nonparametric test. Statistical analysis was performed by ANOVA followed by Dunnett's post hoc test. The 95% confidence level ($P < 0.05$) was considered statistically significant. Data were analyzed using the SPSS statistical software (Statistical Package for the Social Sciences, version 15.0).

3. Results

3.1. 5'-AMP Induces Deep Hypothermia and Reduces Heart Rate in Rats. Three different doses of 5'-AMP were investigated in our study; the vehicle, PBS, was used in the control group. Both the 0.5 mg and 1.0 mg 5'-AMP/g body weight doses reduced the Tb of rats when the Ta was maintained at approximately 15°C (Table 1). Only 1.0 mg/g body weight 5'-AMP induced deep hypothermia at approximately 16°C in rats. The heart rates of anesthetized rats also decreased by approximately 50% within minutes of 5'-AMP administration. During hypothermia, there were no large differences in blood gases, glucose, hemoglobin, and mean arterial blood pressure. These data indicate that the rats entered a safe state of hypometabolism and hypothermia. Because hypometabolism may be beneficial for alleviating metabolic stress after brain ischemic injury, our study was undertaken to examine the possible neuroprotective and anti-inflammatory effects of 5'-AMP-induced hypothermia (AIH) using an MCAO model in rats. The two different doses (0.5 mg/g and 1.0 mg/g body weight) of 5'-AMP were also compared.

3.2. AIH Reduces Cerebral Blood Flow (CBF) after Ischemia/Reperfusion in Rats. During the 90 min occlusion of the middle cerebral artery, local CBF decreased to approximately 51.64 ± 3.08% of baseline in all groups except the sham group. After reperfusion, rapid hyperperfusion (up to 168.67 ± 6.11% of baseline) lasting approximately 30 min was observed in the MCAO, NT, and HT(0.5) groups (Figure 1). The 1.0 mg/g body weight AIH treatment reduced CBF to 138.67 ± 3.29% and 123.50 ± 3.85% of baseline 10 min and 20 min after reperfusion ($P < 0.05$ versus the MCAO, NT, and HT(0.5) groups, Figure 1).

3.3. AIH Reduces Brain Infarct Volume in the Ischemia/Reperfusion Rat Model. Brain infarct volumes were measured by

TABLE 1: 5'-AMP reduces body temperature, heart rate and blood pressure.

	Veh	AMP(1.0)	AMP(0.5)	AMP(0.25)
Before AIH				
pH	7.44 ± 0.04	7.45 ± 0.07	7.43 ± 0.03	7.44 ± 0.05
pCO ₂ (mmHg)	35.67 ± 1.61	36.22 ± 4.12	38.22 ± 5.12	37.16 ± 4.19
pO ₂ (mmHg)	106.42 ± 10.29	110.32 ± 10.12	108.24 ± 8.13	105.34 ± 6.17
Glucose (mg/dL)	118.19 ± 7.24	121.21 ± 12.14	119.34 ± 7.03	129.29 ± 8.44
Hemoglobin (g/dL)	16.25 ± 1.21	15.63 ± 0.91	16.37 ± 0.53	16.12 ± 0.64
MABP (mmHg)	86.12 ± 7.15	85.33 ± 11.12	78.56 ± 12.33	83.82 ± 11.41
HR (beats/min)	378.33 ± 72.33	387.21 ± 52.11	383.09 ± 51.32	362.34 ± 54.76
Temp rect (°C)	36.5 ± 0.11	36.9 ± 0.12	36.7 ± 0.05	36.9 ± 0.03
During AIH				
pH	7.41 ± 0.05	7.39 ± 0.12	7.38 ± 0.11	7.40 ± 0.08
pCO ₂ (mmHg)	41.22 ± 6.11	42.21 ± 3.15	41.38 ± 3.39	41.11 ± 5.19
pO ₂ (mmHg)	93.16 ± 5.61	98.12 ± 7.23	96.11 ± 5.14	99.21 ± 10.26
Glucose (mg/dL)	109.17 ± 5.64	104.73 ± 7.27	98.24 ± 10.24	116.19 ± 11.24
Hemoglobin (g/dL)	18.41 ± 2.15	19.12 ± 1.52	17.22 ± 5.51	19.22 ± 3.64
MABP (mmHg)	79.81 ± 8.61	71.12 ± 10.52	73.17 ± 8.72	78.21 ± 7.21
HR (beats/min)	358.14 ± 53.12	193.38 ± 42.32 ^{**&}	298.24 ± 61.19	332.34 ± 55.22
Temp rect (°C)	36.69 ± 1.39	16.72 ± 1.56 ^{**&}	34.15 ± 2.11	36.61 ± 1.95
After AIH				
pH	7.41 ± 0.05	7.40 ± 0.03	7.39 ± 0.06	7.41 ± 0.03
pCO ₂ (mmHg)	38.02 ± 3.18	35.29 ± 4.21	40.21 ± 3.51	36.21 ± 1.18
pO ₂ (mmHg)	106.76 ± 8.43	115.82 ± 5.92	109.43 ± 9.21	116.24 ± 10.31
Glucose (mg/dL)	110.63 ± 7.92	109.21 ± 10.34	115.41 ± 13.24	117.95 ± 12.95
Hemoglobin (g/dL)	15.33 ± 1.15	16.44 ± 1.62	16.15 ± 1.71	15.72 ± 0.93
MABP (mmHg)	73.12 ± 12.31	71.32 ± 11.35	72.92 ± 4.95	73.14 ± 11.2
HR (beats/min)	364.21 ± 42.42	327.51 ± 32.23	352.01 ± 43.22	356.21 ± 43.25
Temp rect (°C)	36.52 ± 0.11	35.91 ± 0.12	36.71 ± 0.05	36.92 ± 0.03

MABP: mean arterial blood pressure; HR: heart rate; Temp rect: rectal temperature. Values are mean ± SEM, $n = 9$ in each group. * $P < 0.05$ compared to Veh group, [#] $P < 0.05$ compared to AMP(0.5) group and [&] $P < 0.05$ compared to AMP(0.25) group.

TTC staining. To determine the effects of AIH on brain ischemic injury, the infarct size due to ischemic insult was calculated using imaging software. Representative images of infarcted areas (white) are shown in Figure 2(a). In the MCAO group, a large infarcted area was predominantly located in the cerebral cortex and the striatum. The normalized infarct volume in the MCAO, NT, and HT(0.5) groups was $42.15 \pm 1.78\%$, $39.39 \pm 0.98\%$, and $32.22 \pm 0.65\%$, respectively. AIH treatment reduced brain infarct volume to $5.33 \pm 1.30\%$ ($P < 0.05$ versus the MCAO, NT, and HT(0.5) groups, Figure 2(b)).

3.4. AIH Improves Neurological Function after Ischemic Brain Injury. The rotarod test was administered to measure the neurological function of rats after ischemic injury. The time on the rotarod was calculated to determine the effect of AIH treatment. The rats in the MCAO, NT, and HT(0.5) groups remained on the platform for approximately 22.23 ± 1.98 s, 23.17 ± 2.42 s, and 29.22 ± 1.11 s, respectively. AIH treatment improved the time on the platform to 42.29 ± 2.01 s, indicating that AIH treatment significantly attenuated the neurological deficits induced by ischemic brain injury

compared to the MCAO, NT, and HT(0.5) groups ($P < 0.05$, Figure 3).

3.5. AIH Inhibits Apoptosis in the Infarcted Brain. TUNEL staining was used to explore apoptosis in the infarcted area. Brains from rats in the MCAO, NT, and HT(0.5) groups displayed significant numbers of TUNEL-positive nuclei (bright green fluorescence) compared to the sham group (Figures 4(a), 4(b), 4(c), and 4(e)). The number of TUNEL-positive nuclei in the infarcted brains from the HT(1.0) group was reduced to 10.68% of the level observed in the MCAO group (Figure 4(d)). Quantitative analysis indicated that AIH treatment significantly inhibited apoptosis in the infarcted brain area compared to the MCAO, NT, and HT(0.5) groups ($P < 0.05$, Figure 4(f)).

3.6. AIH Decreases Levels of Neutrophil Elastase Infiltration in the Infarcted Brain. Ischemia/reperfusion injury is typically associated with increased inflammation. Sometime the level of neutrophil elastase expression in the infarct area is an indicator of inflammation. Immunofluorescence staining using rat neutrophil-specific antibodies was used to detect

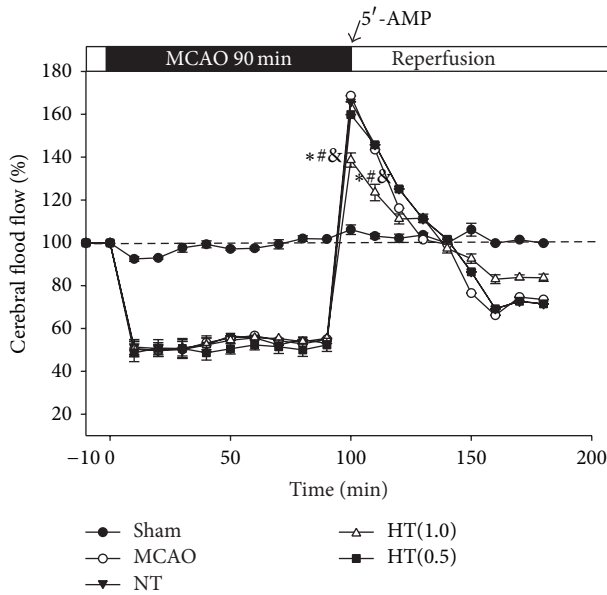


FIGURE 1: AIH reduces cerebral blood flow after ischemia/reperfusion in rats. The trend of CBF in the MCA area after ischemia and AIH was recorded using a laser Doppler flow meter. All values are mean \pm SEM. * $P < 0.05$ compared to the MCAO group, # $P < 0.05$ compared to the NT group, and & $P < 0.05$ compared to the HT(0.5) group.

neutrophil elastase infiltration in all groups. The results indicated that there were few neutrophil elastases expressions in the sham group (Figure 5(a)). In the MCAO control group we found significant upregulation of neutrophil elastases expression in the neuronal cells in the infarcted brain area (Figure 5(b)). The NT group, which was administered 5'-AMP but maintained at a Tb in the euthermic range, exhibited a level of neutrophil elastases similar to that observed in the MCAO control group (Figure 5(c)). The same level of neutrophil elastases was also observed in the HT(0.5) group (Figure 5(e)). Only the HT(1.0) group exhibited significantly decreased levels of neutrophil elastases expression in the neuronal cells in the infarcted brain region (Figure 5(d)). Further quantitative analysis indicated that AIH treatment significantly inhibited neutrophil elastases expression in the neuronal cells in the infarcted brain area compared to the MCAO, NT, and HT(0.5) groups ($P < 0.05$, Figure 5(f)).

3.7. AIH Reduces MMP-9, IL-1R, TNFR, and TLR Protein Expression in the Infarcted Brain. Western blot analysis was performed to detect the levels of the inflammation-related proteins MMP-9, IL-1R, TNFR, and TLR. As with neutrophil infiltration, the MMP-9, IL-1R, TNFR, and TLR protein levels were increased in the MCAO control group and the NT group (Figure 6(a)). The dose of 0.5 mg 5'-AMP/g body weight also did not reduce the MMP-9, IL-1R, TNFR, and TLR levels (Figure 6(a)). A greater reduction of MMP-9, IL-1R, TNFR, and TLR expression was observed in the 1.0 mg 5'-AMP/g body weight treatment group (Figure 6(a)). To confirm this observation, β -actin levels were used as an

internal reference for quantitative analysis. These data indicate that AIH treatment significantly reduced MMP-9, IL-1R, TNFR, and TLR protein levels in the infarcted brain area compared to the MCAO, NT, and HT(0.5) groups ($P < 0.05$, Figure 6(b)).

4. Discussion

In agreement with previous studies [10], this study demonstrated that a high dose of 5'-AMP could reduce the Tb to approximately 16°C under appropriate Ta. Controlling Ta is a useful way to regulate an animal's Tb after administration of 5'-AMP. For example, rats given 5'-AMP but kept at a Ta of 33°C, such as the NT group, can maintain their Tb in the euthermic range. However, when the Ta was maintained at 15°C, the Tb of the rats dropped to approximately 16°C. This synchronous change in Tb with the administration of 5'-AMP renders 5'-AMP a good agent for the induction of hypothermia. Thus, in the present study, we examined the effects of AIH treatment on brain ischemic injury in rats. AIH treatment reduced brain infarct volume, improved neurological function, and inhibited neuronal apoptosis. Further experiments indicated that AIH treatment induced a significant inhibition of neutrophil infiltration into the infarcted brain area and a significant reduction in MMP-9, IL-1R, TNFR, and TLR protein levels in the ischemic brain. Taken together, these data suggest that AIH treatment has a neuroprotective effect in focal brain ischemic injury and that this effect is mediated by inhibition of an inflammatory reaction.

The concept of neuroprotection has generated much enthusiasm over the past two decades and has triggered a substantial amount of research focused on its use in the treatment of ischemic stroke [12]. It has been suggested that therapeutic hypothermia may be the most potent neuroprotective strategy [13, 14]. A potential advantage of therapeutic hypothermia over other methods for neuroprotection is its ability to activate numerous pathways simultaneously by several mechanisms during the ischemia and reperfusion windows and to reduce damage beyond the neuron, within the entire neurovascular unit. Mild hypothermia treatment reduces brain infarct size in several ischemic animal models [3, 15]. However, a previous study in rats using 5'-AMP to reduce Tb to approximately 33-34°C for 2.5 h did not yield a beneficial outcome in a model of transient cerebral ischemia [16]. By contrast, we determined that 5'-AMP could reduce the Tb to approximately 16°C in rats and maintain that temperature for approximately 6 h with low Ta. A low Ta not only reduced Tb but also decreased the required dose of 5'-AMP. Mammals may differ in their preference for the torpor state, depending on their metabolic rates [17, 18]. Large mammals, such as bears, technically do not hibernate but instead undergo torpor at a Tb of approximately 32°C, while small rodents can hibernate at a Tb of less than 10°C. Thus, we suggest that small rodents, such as mice and rats, that have high metabolic rates must be cooled to much lower than 34°C, even to approximately 10°C, to prevent ischemic injury.

Inflammation is a central component in the pathophysiology of cerebral ischemic injury [19]. Brain ischemia triggers both local and systemic inflammatory responses. Studies have

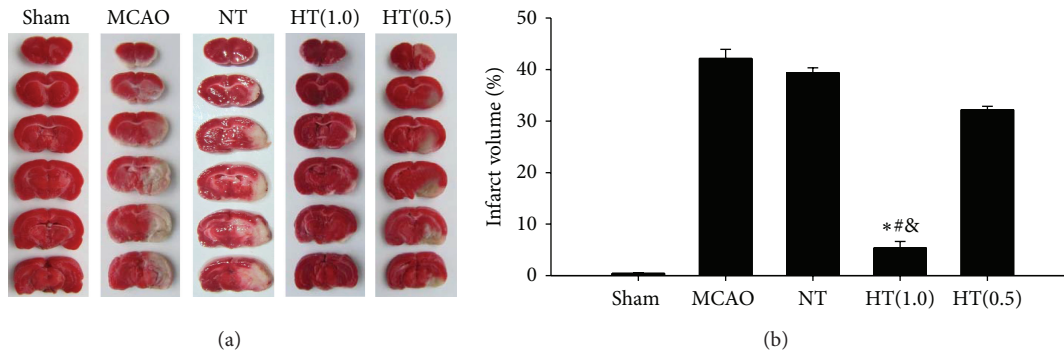


FIGURE 2: AIH reduces brain infarct volume in the ischemia/reperfusion rat model. TTC staining was used to measure the brain infarct volume 24 h after reperfusion. (a) Representative infarct volume stained with TTC in each group. (b) Average infarct volume in rats treated with 5'-AMP coupled with low Ta. All values are mean \pm SEM. * $P < 0.05$ compared to the MCAO group, # $P < 0.05$ compared to the NT group, and & $P < 0.05$ compared to the HT(0.5) group.

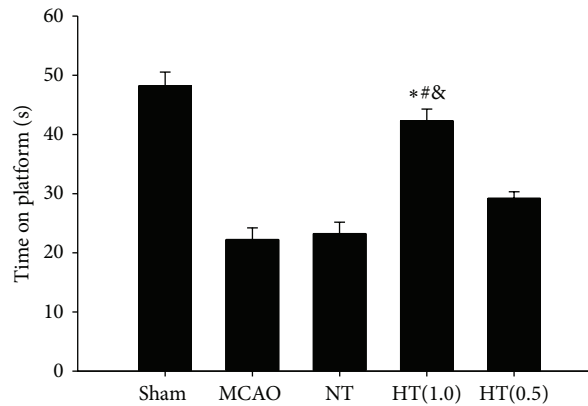


FIGURE 3: AIH improves neurological function after brain ischemic injury. The neurological function of rats after ischemic injury was evaluated using the rotarod test. All values are mean \pm SEM. * $P < 0.05$ compared to the MCAO group, # $P < 0.05$ compared to the NT group, and & $P < 0.05$ compared to the HT(0.5) group.

suggested that brain ischemic injury caused by cerebral blood occlusion followed by reperfusion is neutrophil-dependent [20]. One crucial factor underlying ischemic damage during the reperfusion phase is neutrophil infiltration. Thus, one strategy for attenuating ischemic brain injury is to use treatments targeting neutrophils, such as antineutrophil drugs and anti-neutrophil antibodies.

Neutrophil elastase (NE), a kind of leukocyte-derived proteases, degrades the basement membrane to allow neutrophil extravasation and infiltration. Therefore, in our study, we would like to show if NE could injure or infiltrate the neuron in the infarcted area after brain ischemic injury. Then we aimed to investigate if 5'-AMP-induced hypothermia could attenuate this NE-mediated injury. As we all know, leukocyte-derived proteases, such as NE, degrade the basement membrane to allow leukocyte extravasation into the surrounding tissue, jeopardizing BBB integrity in the process. In addition, some studies [21, 22] have discussed the role of NE in injury of neuronal cells. Once present in the parenchymal extracellular space, NE may also degrade additional extracellular matrix substrates (e.g., collagens, laminins) to threaten neuronal and glial viability. In our study, we also found that NE could

invade into the antineuronal nuclei positive cells. Although the exact mechanism is still not clear, the hypothermia could attenuate the invasion. Our further study will use NE-null mice or pharmacologic inhibition of NE to investigate which signal pathway will be involved in this NE-related neuronal injury.

However, randomized clinical trials of anti-inflammatory agents in ischemic patients have not demonstrated a significant neuroprotective effect [23, 24]. A potential reason for the poor outcomes of these studies is that the inflammation cascade triggered by brain ischemia involves many different chemokines and cytokines. Inflammation is triggered by receptors of the innate immune system, including Toll-like receptors (TLRs) or cytokine receptors such as tumor necrosis factor receptor (TNFR) and interleukin-1 receptor (IL-1R). Activation of these pathways results in the induction of inflammatory genes that are mediators or effectors of the ischemic stimulus. Systemic hypothermia induced by AIH treatment may represent a better approach to inhibiting inflammation by reducing a broad array of inflammatory responses. In our study, we observed that AIH treatment

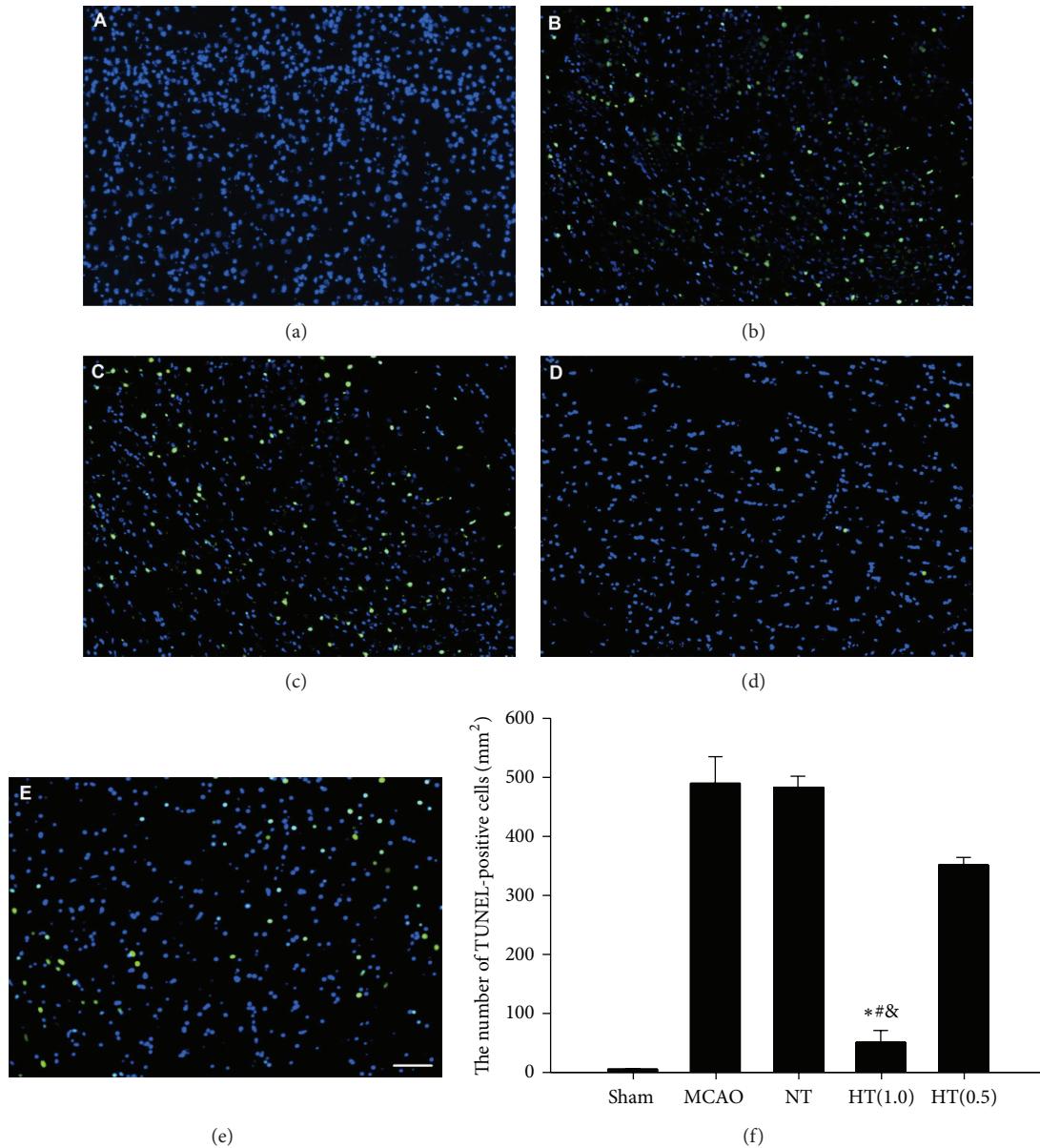


FIGURE 4: AIH inhibits neuronal apoptosis in the infarcted brain. (a–e) Fluorescence results of the TUNEL assay in the sham, MCAO, NT, HT(1.0), and HT(0.5) groups. Bright green dots were deemed apoptotic cells. Scale bar = 50 μm . (f) Quantitative analysis of apoptotic cells 24 h after ischemia. TUNEL-positive cells were counted from 3 random $1 \times 1 \text{ mm}^2$ areas. All values are the mean \pm SEM. * $P < 0.05$ compared to the MCAO group, # $P < 0.05$ compared to the NT group, and & $P < 0.05$ compared to the HT(0.5) group.

reduced the protein levels of the initial inflammatory receptors IL-1R, TNFR, and TLR. These receptors are known to induce proinflammatory gene expression, microglial and endothelial activation, and leukocyte infiltration.

Activation of matrix metalloproteinases (MMPs), the largest class of human proteases, plays an important role during the early stage of ischemic brain injury [25]. Accumulating data suggest that MMPs are actively involved in the inflammatory process [26, 27]. MMPs are believed to have an impact on many of the cytokines and chemokines involved in the inflammatory response, often with apparently opposing outcomes. Activated MMP-9 colocalizes with infiltrating

neutrophils after brain ischemia and reperfusion. Dual MMP/neutrophil elastase (NE) inhibitors reduce endotoxin-driven airway cellular inflammation in vivo [28, 29]. Synthesized MMP inhibitors and several compounds used for secondary stroke prevention, such as anti-inflammatory drugs, could potentially reduce MMP activity and improve the acute treatment of brain ischemia in humans. Our studies suggest that AIH treatment attenuates ischemia/reperfusion injury by reducing both MMP-9 protein levels and neutrophil infiltration.

Apoptotic cell death plays an important role in inflammatory processes and in the resolution of inflammatory

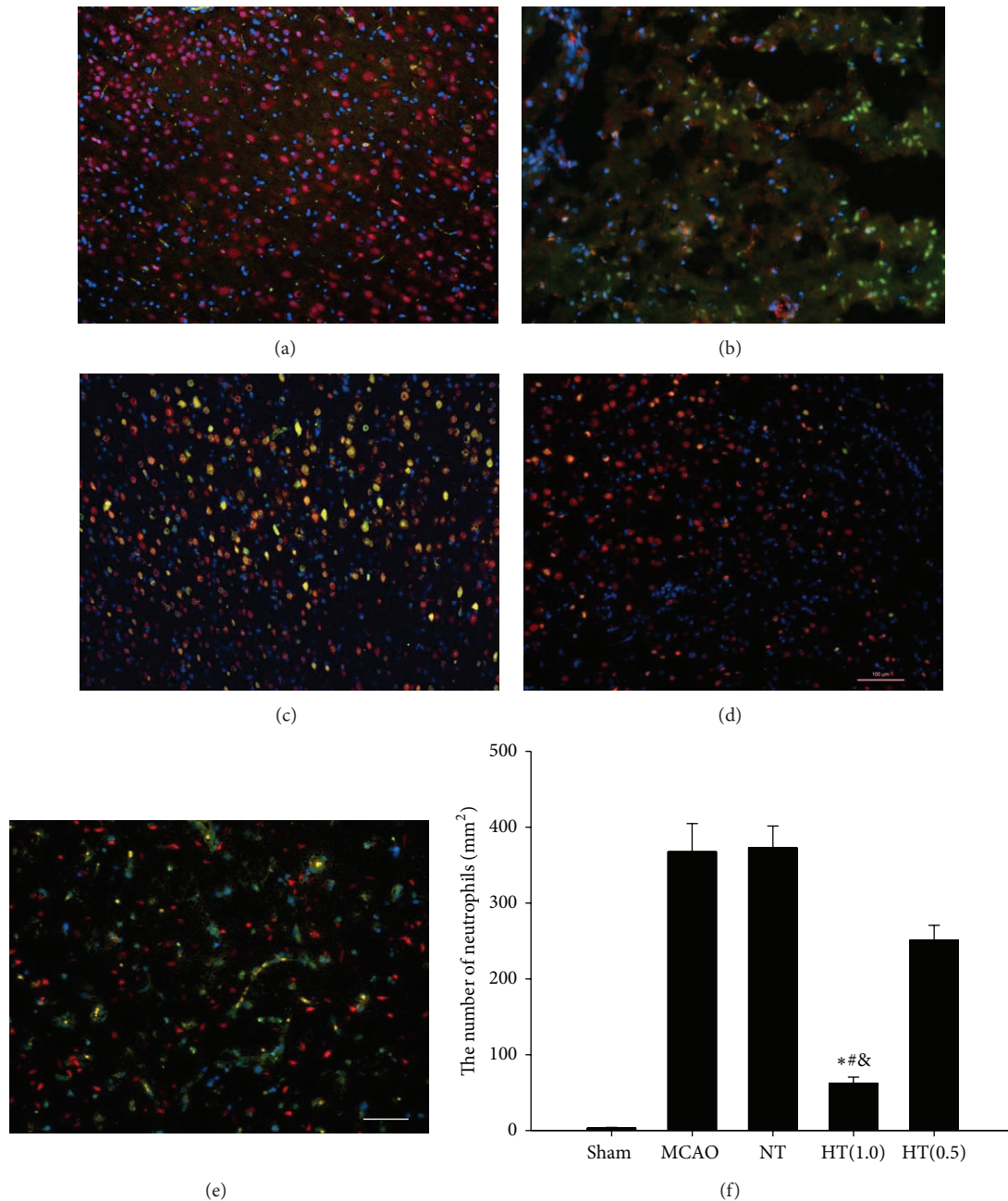


FIGURE 5: AIH decreases levels of neutrophil elastase expression in the infarcted brain. Coronal sections 24 h after operation were stained with specific antibodies: neutrophil elastase (green) and NeuN (red). The mounting medium contained DAPI, which counterstained the nuclei (blue). The merged images show the coexpression of NeuN and neutrophil elastase in yellow (a–e). Scale bar = 100 μm . (f) Neutrophil elastase-positive cells were quantitatively analyzed using ImageJ software. All values are the mean \pm SEM. * $P < 0.05$ compared to the MCAO group, # $P < 0.05$ compared to the NT group, and & $P < 0.05$ compared to the HT(0.5) group.

reactions [30]. Multiple in vivo studies have demonstrated the attenuation of ischemic reperfusion injury through the inhibition of apoptosis [31]. Hypothermia may protect against neuronal apoptosis induced by ischemic injury by inhibiting both extrinsic and intrinsic signaling pathways. Our studies demonstrate that neuronal apoptosis is largely prevented by AIH treatment.

Reduction of the brain workload is thought to be beneficial in brain ischemia. We previously suggested that the bradycardia effect of 5'-AMP is not driven by dephosphorylation of 5'-AMP to form adenosine but rather by the induction of hypothermia in mice [10]. In the present study, we observed the same bradycardia effect in rats after administration of 5'-AMP. After recanalization to restore CBF, CBF can increase

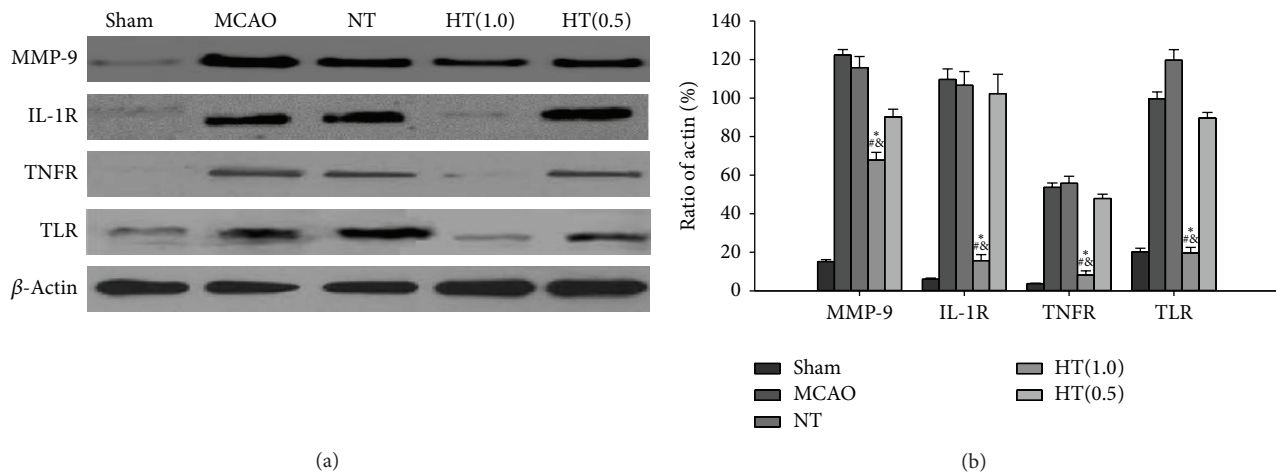


FIGURE 6: AIH reduces MMP-9, IL-1R, TNFR, and TLR protein levels in the infarcted brain. (a) Western blot analysis of protein expression of MMP-9, IL-1R, TNFR, and TLR in the sham, MCAO, NT, HT(1.0), and HT(0.5) groups. β -Actin was used as an internal reference. (b) Optical density analysis of MMP-9, IL-1R, TNFR, and TLR. All values are the mean \pm SEM. * $P < 0.05$ compared to the MCAO group, # $P < 0.05$ compared to the NT group, and & $P < 0.05$ compared to the HT(0.5) group.

to above baseline levels in cerebral ischemia. Postischemic hyperperfusion is a sequel of ischemic damage in regions that are likely to undergo infarction. Using a CBF monitor, we demonstrated that 5'-AMP administration reduces CBF after ischemia/reperfusion injury in rats. AIH treatment attenuated the state of rapid hyperperfusion observed upon increased CBF, particularly after reperfusion.

In conclusion, our present study tested the neuroprotective effect of 5'-AMP administration in a rat model of brain ischemia/reperfusion. By controlling Ta, 5'-AMP safely induced a reversible deep hypothermia that reduced ischemic injury following focal brain ischemia in rats. The neuroprotective effects of AIH were shown to be related to the anti-inflammatory effect of AIH.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

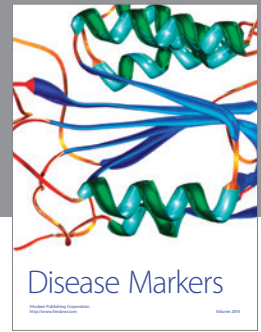
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