

Research paper

Caffeine inhibits hypoxia-induced nuclear accumulation in HIF-1 α and promotes neonatal neuronal survivalHsiu-Ling Li^{a,b,*}, Nahla Zaghloul^{c,d}, Ijaz Ahmed^b, Anton Omelchenko^{e,f}, Bonnie L. Firestein^e, Hai Huang^b, Latoya Collins^b^a Department of Physiology and Pharmacology, SUNY-Downstate Medical Center, New York, United States^b Department of Biology, Medgar Evers College, City University of New York, United States^c Cohen Children's Medical Center, Northwell Health, New Hyde Park, New York, United States^d Feinstein Institute for Medical Research, Northwell Health, Manhasset, New York, United States^e Department of Cell Biology and Neuroscience, Rutgers, The State University of New Jersey, Piscataway, New Jersey, United States^f Neuroscience Graduate Program, Rutgers, The State University of New Jersey, Piscataway, New Jersey, United States

A B S T R A C T

Apnea of prematurity (AOP) defined as cessation of breathing for 15–20 s, is commonly seen in preterm infants. Caffeine is widely used to treat AOP due to its safety and effectiveness. Caffeine releases respiratory arrest by competing with adenosine for binding to adenosine A₁ and A_{2A} receptors (A₁R and A_{2A}R). Long before its use in treating AOP, caffeine has been used as a psychostimulant in adult brains. However, the effect of caffeine on developing brains remains unclear. We found that A₁R proteins for caffeine binding were expressed in the brains of neonatal rodents and preterm infants (26–27 weeks). Neonatal A₁R proteins colocalized with PSD-95, suggesting its synaptic localization. In contrast, our finding on A_{2A}R expression in neonatal neurons was restricted to the mRNA level as detected by single cell RT/PCR due to the lack of specific A_{2A}R antibody. Furthermore, caffeine (200 μ M) at a dose twice higher than the clinically relevant dose (36–130 μ M) had minor or no effects on several basic neuronal functions, such as neurite outgrowth, synapse formation, expression of A₁R and transcription of CREB-1 and c-Fos, further supporting the safety of caffeine for clinical use. We found that treatment with CoCl₂ (125 μ M), a hypoxia mimetic agent, for 24 h triggered neuronal death and nuclear accumulation of HIF-1 α in primary neuronal cultures. Subsequent treatment with caffeine at a concentration of 100 μ M alleviated CoCl₂-induced cell death and prevented nuclear accumulation of HIF-1 α . Consistently, caffeine treatment in early postnatal life of neonatal mice (P4–P7) also prevented subsequent hypoxia-induced nuclear increase of HIF-1 α . Together, our data support the utility of caffeine in alleviating hypoxia-induced damages in developing neurons.

1. Introduction

Apnea of prematurity (AOP), defined as cessation of breathing for > 20 s, is commonly seen in preterm infants (≤ 30 weeks of gestation). Preterm infants have a higher incidence of apnea due to exaggerated inhibition of the respiratory rhythm by adenosine signaling (Mathew, 2011). Methylxanthines, including caffeine, have been used to treat AOP for 40 years. Caffeine effectively releases this respiratory arrest by competing with adenosine for binding to adenosine receptors (Bairam et al., 1987). Clinically, relatively high concentrations of caffeine are used to treat AOP. The plasma concentrations of caffeine in preterm infants during AOP treatment were shown to be 10–100 times higher than that in infants receiving breast milk from mothers who drank moderate doses of coffee (Aden, 2011). The efficacy of caffeine was not evaluated until recently by a multicenter trial led by Erenberg and colleagues and by the international trial on caffeine for apnea (CAP trial) (Erenberg et al., 2000; Schmidt, 2005). The CAP trial suggested

that caffeine is beneficial in lowering the incidence of several short-term morbidities, including bronchopulmonary dysplasia, and improving neurodevelopmental outcomes of premature infants at 18 to 21 months of age (Schmidt et al., 2007). These clinical trials not only validated the use of caffeine in alleviating AOP but also suggested that neonatal caffeine treatment may be beneficial to neurodevelopment in preterm infants.

Caffeine has been used to stimulate adult brains as a psychostimulant long before its use in treating AOP (Ferre, 2016; Frary et al., 2005). It is thought to modulate adult brain activity and plasticity by directly perturbing the purinergic system and indirectly affecting the transmission of other neurotransmitters (Fredholm et al., 1999). However, the effects of caffeine on developing brains remain unclear, especially when preterm infants receive such high concentrations of caffeine during AOP treatment.

Hypoxic ischemia is one of the major causes of early brain injury, which affects around 0.1–0.3% of term infants and the incidence in

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preterm infants is 0.1–0.8% (Davidson et al., 2018). Therapeutic strategies to treat early brain injury include neuroprotective agents and plasticity enhancing agents for functional recovery. Caffeine has been suggested to have both effects: 1) caffeine has been suggested to be neuroprotective in both rodents and preterm infants (Back et al., 2006; Cunha, 2001; Ferreira and Paes-de-Carvalho, 2001; Fredholm et al., 2011; Rivkees and Wendler, 2011; Winerdal et al., 2017) (Schmidt et al., 2007) and 2) caffeine is known to modulate plasticity in adult brains (Fredholm et al., 1999). We therefore propose that caffeine is a candidate agent for alleviating the damages caused by hypoxia ischemia in neonatal brains.

Adenosine A₁ and A_{2A} receptors (A₁R and A_{2A}R) are the primary targets of caffeine (Fredholm et al., 1999). Thus, characterizing the expression of these receptors in neonatal brains is essential before testing the effects of caffeine for treating early brain injury. A₁R and A_{2A}R can be detected in rat brains at perinatal stages by *in situ* hybridization and radioactive ligand binding assays, albeit at lower levels compared to adult brains (Aden et al., 2000, 2001; Rivkees, 1995). However, the protein expression and subcellular localization of these receptors in the brain have not been identified in neonatal rodents and preterm infants. Using an antibody specifically against A₁R in wild type mice, but not in A₁R deficient mice, we found that A₁R displayed a punctate staining pattern and were synaptically localized in the brains of both neonatal mouse pups (postnatal day 3) and preterm infants (corrected age of 26–27 weeks). In contrast to A₁R, the localization of A_{2A}R in neonatal brains remains unclear due to the poor specificity of tested antibodies against A_{2A}R. Furthermore, we also demonstrated the safety and therapeutic effects of caffeine on neonatal neurons. We found caffeine at a concentration of 200 μ M did not affect basic neuronal functions, such as 1) expression and distribution of adenosine receptor, A₁R, 2) mRNA levels of transcription factors, CREB-1, c-Fos and HIF-1 α , and 3) neurite outgrowth and synapse formation. Importantly, we found that at a clinically relevant dose, caffeine promoted survival of primary neurons after hypoxic insults and prevented hypoxia-induced accumulation of HIF-1 α both in primary culture (100 μ M of caffeine) and in neonatal mouse pups (estimated serum concentration of caffeine is 26–77 μ M).

2. Materials and methods

The protocols for animal experiments were approved by IACUC at SUNY Downstate Medical Center, Rutgers University and Feinstein Medical Institute. The use of autopsy specimens of preterm brain tissue from the neuropathology laboratory was approved by IRB at Cohen Children's Medical Center.

2.1. Primary neuronal cultures

Primary neuronal cultures were prepared from E18 or P8 rat pups as described. Briefly, the hippocampus, cerebellum or cortex was dissected followed by trypsinization and centrifugation. The pellet was then resuspended in neuronal culture medium (Neurobasal medium supplemented with 2% B27 and 25 mM KCl) and seeded at a density of 5×10^5 cells/ml (for RT/PCR and immunostaining) or 1×10^5 cells/ml (for MTT assays).

2.2. Induction of hypoxia *in vitro*

Cobalt chloride (CoCl₂·6H₂O) (Sigma) was used to induce hypoxia in primary neuronal cultures as previously described (Wu and Yotnda, 2011). Five-day old neuronal cultures were treated with various concentrations of CoCl₂ (50–125 μ M) for 24 h. After washing off the CoCl₂, cultures were replenished with conditioned medium which was supplemented with 100 μ M caffeine or vehicle control for an additional 24 h, followed by fixation and analysis.

2.3. Neonatal hypoxia and caffeine treatment *in vivo*

Mouse pups were given caffeine at a loading dose of 20 mg/kg/day on postnatal day 4 (P4), then 15 mg/kg/day for the next 3 days. Caffeine was dissolved in sterile water and given to mouse pups via orogastric tube 1.9 french to maintain a serum concentration of caffeine at 5–15 mg/l (approximately 26–77 μ M) (Gaytan et al., 2006; Guillet and Kellogg, 1991). Sham groups were given equal volumes of sterile water via the orogastric route. In both groups, half of the pups were exposed to hypoxic environment (8% oxygen) for 20 min on P7, whereas the other half remained in normoxia. Pups were then deeply anesthetized with a lethal dose of xylazine (30 mg/kg)/ketamine (300 mg/kg) and perfused transcardially with 4% PFA.

2.4. Immunostaining

Immunostaining was performed using antibodies against A₁R or A_{2A}R (Antibody Online, GA and Genetex, CA and AbCam, MA), PSD-95 (Santa Cruz, CA), beta-III tubulin (Sigma), AMPA, CREB-1 and syntaxin (all from Genescript, NJ), HIF-1 α (Novus, CO, Genetex, CA and AbCam, MA) and c-Fos (Genetex, CA and Biorbyt, CA). The immune complexes were detected by FITC-conjugated anti-mouse antibodies or Cy3-conjugated goat anti-rabbit antibodies (Jackson ImmunoResearch, PA). The resulting images were acquired using Axiovert fluorescent microscopy (primary neuronal cultures), Zeiss LSM710 (mouse brains) or Olympus Fluoroview 300 (preterm infant brains) confocal microscopy. The brains of mice deficient in A₁R or A_{2A}R were kindly provided by Dr. William Welch (Georgetown University) and Dr. Bruce Cronstein (NYU), respectively.

Unless specified, all mouse brains were immunostained using vibratome sections (50 μ m thick). For A₁R and PSD-95 co-localization experiments, cryosectioned slices were used. For study of the expression of A₁R in postmortem preterm human brain, tissues were collected from the autopsy specimens of preterm infants (gestational age of 23–24 weeks) who were given caffeine on the first day of life and continued until death at three weeks of life. These tissues were fixed in 10% formalin, paraffin embedded and sectioned coronally at 6 μ m thick. Following antigen retrieval, sections were incubated with A₁R antibody.

The densitometries of single cell RT-PCR bands and the neurite length in the acquired images of beta-III tubulin immunostaining were quantified using NIH ImageJ. The number of A₁R, syntaxin and AMPAR puncta was quantified using the Analyze Particle function of Fiji ImageJ (size = 30–250, circularity = 0.3–1.0) as previously described (Muller et al., 2018; Taylor et al., 2010). The pixel intensity of HIF-1 α in the nucleus and cytoplasm was measured using ImageJ.

2.5. MTT viability assay

Primary neurons were seeded at a concentration of 1×10^5 cells/ml and cultured for 7 days prior to the addition of 125 μ M of CoCl₂ for an additional 24 h. CoCl₂ containing medium was then replaced with conditioned medium in the presence or absence of 100 μ M caffeine for an additional 24 h. Neuronal viability was tested using the MTT assay as follows.

MTT [3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide] was added to medium at a final concentration of 0.5 mg/ml and incubated with the cells at 37 °C for 2 h. The resulting purple crystals (due to the action of mitochondrial reductase) were solubilized with DMSO and the optical density at 570 nm was subsequently measured.

2.6. Single cell RT-PCR

Glass cover slips coated with poly-L-lysine (Sigma) were cut at dimensions of approximately 2×3 mm. These cover slips were placed in 24 well tissue culture plates. Primary neurons were then seeded at a

density of 5×10^5 cells/ml. After 48 h, caffeine was added to the medium for an additional 5 days. Based on the morphology, cover glasses containing single neurons were harvested for RT-PCR as previously described (Dulac and Axel, 1995; Li et al., 2009). Reactions that were positive for the expression of GFAP, a glial cell marker, were discarded. All PCR products were subjected to sequencing analysis. The primers used to amplify the corresponding fragment of the genes are listed in the following table.

Gene (Gene bank no.)	Primers
Adenosine A ₁ Receptor (NM64299)	F: ACC TGC CTC ATG GTG GCC TG R: GTA GTA CTT CTG GGG GTC ACC G
Adenosine A _{2A} Receptor (AF2228684)	F: GGA GCT GGC CAT CGC TGT GC R: TCG CCG CAG GTC TTC GTG GA
Actin (NM031144)	F: CCC TGT GCT GCT CAC CGA GG R: GCG GCA GTG GCC ATC TCT TG
CREB-1 (NM_031017.1)	F: GGG CAG ACA GTC CAG GTC CAT R: GCC AGC TGT ATT GCT CCT CCC
C-Fos (NM_022197)	F: ACG AGG CGT CAT CCT CCC GCT R: CCG TCC TCC GAT TCC GGC AC
HIF-1 α (NM_24359.1)	F: GCA GCA CGA TCT CGG CGA AGC R: CAT CGT CCT CCC CCG GCT TG

2.7. Statistics

Data were analyzed using GraphPad Prism 7 software (GraphPad Software Inc., CA.). Student's *t*-test was used to compare the data of two experimental groups, whereas the data of more than two groups were analyzed by ANOVA. The values of $p < 0.001$ were considered statistically significant. All data are shown as mean $\pm$ SEM.

3. Results

3.1. Adenosine A₁ receptors are synaptically localized in neonatal brains

We first asked whether the brains of both neonatal mice and preterm infants express the primary receptors for caffeine, adenosine receptors A₁R and A_{2A}R by immunostaining. We chose immunostaining instead of Western blotting because Western blotting does not show the subcellular localization of these receptors and the tissue extracts often include non-neuronal cell types.

We screened the specificity of several commercially available antibodies against A₁R and A_{2A}R. We chose antibodies that showed high immunoreactivity in wild type mouse brains but not in the brains of the corresponding knockout mice. Using two antibodies against different epitopes of A₁R, we consistently observed A₁R distributed in a punctuate pattern in adult wild type brains (25.33 ± 2.40 puncta), but not in A₁R-deficient brains (8.67 ± 0.88 puncta, $p < 0.001$) (Fig. 1A, top panel; enlarged images are in Supplementary Fig. S1A).

In contrast to A₁R, several commercially available antibodies against A_{2A}R displayed low specificity, showing intense nuclear staining in both wild type and A_{2A}R knockout brains (Fig. 1A, bottom panel; enlarged images are in Supplementary Fig. S1A). Thus, this study focused mainly on A₁R, but not A_{2A}R, in neonatal brains.

Similar to adult brain tissues, we found A₁R also distributed in a punctate pattern in neonatal cortex (Fig. 1B). This punctate pattern can be detected in neonatal mouse cortex as early as postnatal day 3 (P3), albeit the puncta are smaller in size compared to those in older pups (P10 and 1 month old) (Fig. 1B; an enlarged image of P3 brain is in Supplementary Fig. S1B). In addition to cortex, A₁R was also expressed in a similar punctate pattern in various brain regions, such as medulla, cerebellum, thalamus and hippocampus (Fig. 1C; an enlarged image of medulla is in Supplementary Fig. S1C). A₁R puncta were most prominent in medulla and cerebellum (Fig. 1C), but weak in basal ganglia (data not shown). The punctuate pattern of A₁R is reminiscent of that of synaptic markers. Using double immunostaining, we found that A₁R co-

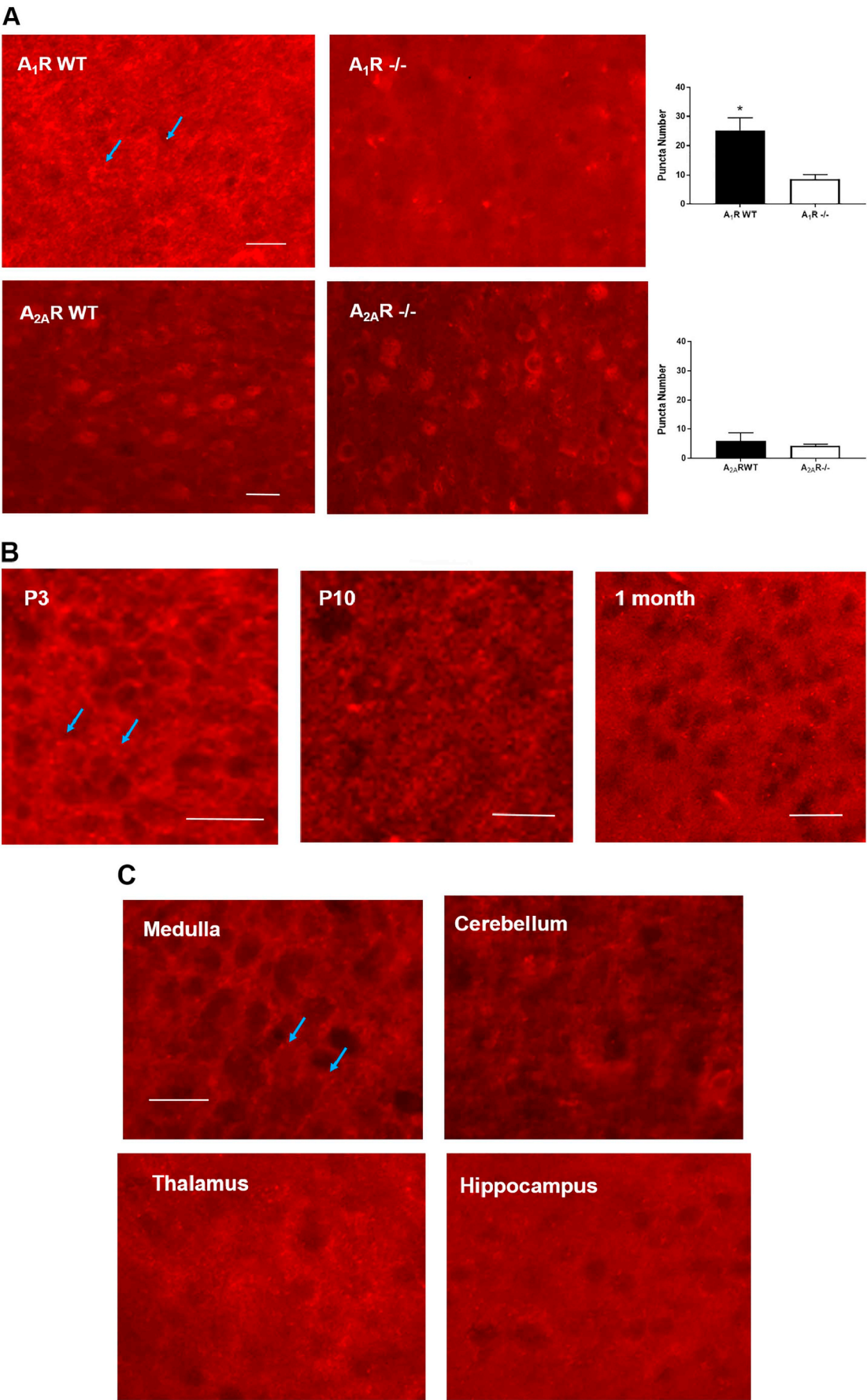
localized with PSD-95, a synaptic protein, suggesting A₁R is synaptically localized in neonatal mouse brain (the earliest time point we studied is P3) (Fig. 1E, top panel; an enlarged image is in Supplementary Fig. S1E).

We next sought to extend our findings to postmortem preterm brains. Most deceased preterm infants in our clinics were born at approximately gestational age of 23–24 weeks and died at the corrected age of 26–27 weeks. Among these patients, we selected infants with no discernible brain abnormalities on head ultrasound. It is worth noting that all selected infants received caffeine since it is our policy that all preterm infants with gestational age younger than 29 weeks be given caffeine within hours after birth. We therefore did not have age-matched preterm infants who did not receive caffeine among this age group. However, we still found detectable levels of A₁R puncta in these preterm brains, as demonstrated in the cortex of 6 different preterm infants (a representative section of each patient is shown in Fig. 1D; an enlarged image is in Supplementary Fig. S1D). These A₁R puncta co-localized with PSD-95 (Fig. 1E, bottom panel). Together, these data supported the hypothesis that the preterm brain may be influenced by caffeine during therapy to treat AOP.

3.2. Caffeine promotes cell survival and suppresses hypoxia-induced nuclear accumulation of HIF-1 α in vitro

Caffeine has been suggested to be neuroprotective, but its safety and effectiveness in neonatal neurons remained unclear (Aden, 2011; Natarajan et al., 2007; Rivkees and Wendler, 2011; Schmidt et al., 2007; Winerdal et al., 2017). Here, we sought to address these issues both *in vitro* and *in vivo*. When investigating whether caffeine perturbs the general neuronal functions, we used a higher concentration of caffeine (200–400 μ M). However, we returned to the clinically relevant doses of caffeine (50–100 μ M) to evaluate its neuroprotective effects on primary neurons after ischemic insults.

We examined three neuronal aspects to gauge the safety of caffeine: 1) expression of A₁R and A_{2A}R, 2) levels of several transcription factors, CREB-1, c-Fos and HIF-1 α , and 3) synapse formation and neurite outgrowth. First, we analyzed the effects of caffeine on the transcription of A₁R and A_{2A}R by single cell RT/PCR as well as their protein levels by immunostaining. To ensure specificity, all RT/PCR products were sequenced to verify the identity of adenosine A₁R and A_{2A}R. The intensities of the PCR products were quantified using the densitometry function of ImageJ in arbitrary units. We found that neonatal neuronal cultures expressed mRNA for both adenosine A₁R and A_{2A}R in untreated controls (2104 ± 138 and 2446 ± 130). With 200 μ M caffeine treatment, the transcription of A₁R and A_{2A}R was comparable to that of untreated neurons (2000 ± 136 and 2500 ± 150). However, when the concentration of caffeine was raised to 400 μ M, caffeine selectively impaired the transcription of A₁R, but not A₂R (360 ± 0.3 and 2280 ± 77) (Fig. 2A). Second, caffeine treatment was suggested to regulate the expression of several transcription factors, such as c-Fos, CREB-1, and HIF-1 α (Connolly and Kingsbury, 2010; Gaytan and Pasaro, 2012) (Maugeri et al., 2018; Merighi et al., 2007). CREB-1 and c-Fos are immediate early genes induced by neural activity, whereas HIF-1 α is often induced by hypoxic conditions. We examined the effects of caffeine on these transcription factors in neuronal cultures under normoxic conditions using single cell RT/PCR. In the absence of caffeine, there was low baseline expression of c-Fos but higher levels in HIF-1 α and CREB-1 mRNA (HIF-1 α , 2978 ± 17.5 ; CREB-1, 2928 ± 64 ; c-Fos, 105 ± 7.5) (Fig. 2A). With treatment of either 200 μ M or 400 μ M caffeine, we did not observe any significant changes in the transcription of HIF-1 α , CREB-1 and c-Fos (HIF-1 α , 3141 ± 193 and 3095 ± 111 ; CREB-1, 2933 ± 88 and 3007 ± 64 ; c-Fos, 132 ± 7.6 and 114 ± 4) (Fig. 2A). Third, beta-III tubulin and syntaxin are commonly used markers for the measurement of neurite length and synaptogenesis (Katsetos et al., 2003; Shin, 2014). We found that the average neurite length ($162.1 \pm 17.45 \mu$ m) and the number of



(caption on next page)

Fig. 1. The brains of neonatal mice and preterm infants expressed A₁R receptors. (A) Immunostaining results showed the specificity of A₁R antibody but not A_{2A}R antibody. Using the tested A₁R antibody, A₁R immunostaining showed a punctate distribution of this receptor in the cortex of wild type adult mice, but not in that of A₁R deficient mice (25.33 ± 2.4 and 8.67 ± 0.88 puncta, respectively) (top). In contrast, several antibodies against A_{2A}R showed non-specific immunoreactivity in the nucleus and the cytoplasm in both wild type and A_{2A}R deficient mice (bottom). No punctate pattern was observed (6 ± 1.53 puncta for WT and 4.33 ± 0.3 puncta for A_{2A}R knockout). Representative images are shown here. The quantitative results are shown on the right. Blue arrows indicate puncta. Scale bar, 10 μ m. (B) The punctate pattern of A₁R could be detected in the cortex of P3 pups. The A₁R puncta appeared more discrete at a lower magnification as the animals mature (10 day-old and 1 month-old pups). (C) A₁R distributed in a punctate pattern in medulla, cerebellum, thalamus and hippocampus. The puncta were more prominent in medulla and cerebellum. Scale bar, 20 μ m. (D) Immunostaining showed a punctate pattern of A₁R in the cortex of preterm infants at the corrected age of 26–27 weeks. Representative images of the cortex from 6 preterm brains are shown. Scale bar, 10 μ m. (E) A₁R colocalized with a synaptic protein, PSD-95, in frozen sections of neonatal mouse brain (upper panel) and paraffin sections of preterm infant brains (lower panel). Scale bar, 20 μ m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

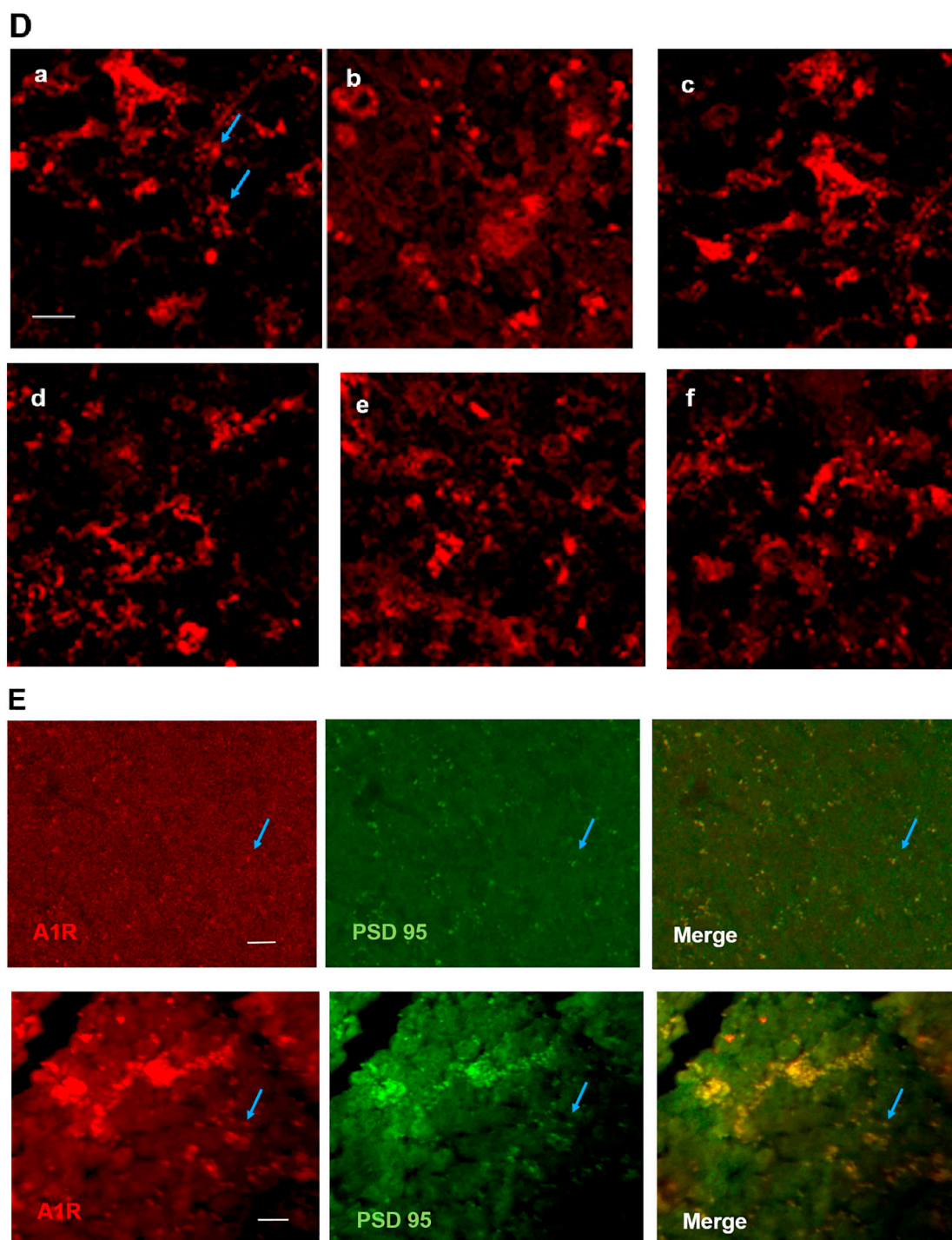


Fig. 1. (continued)

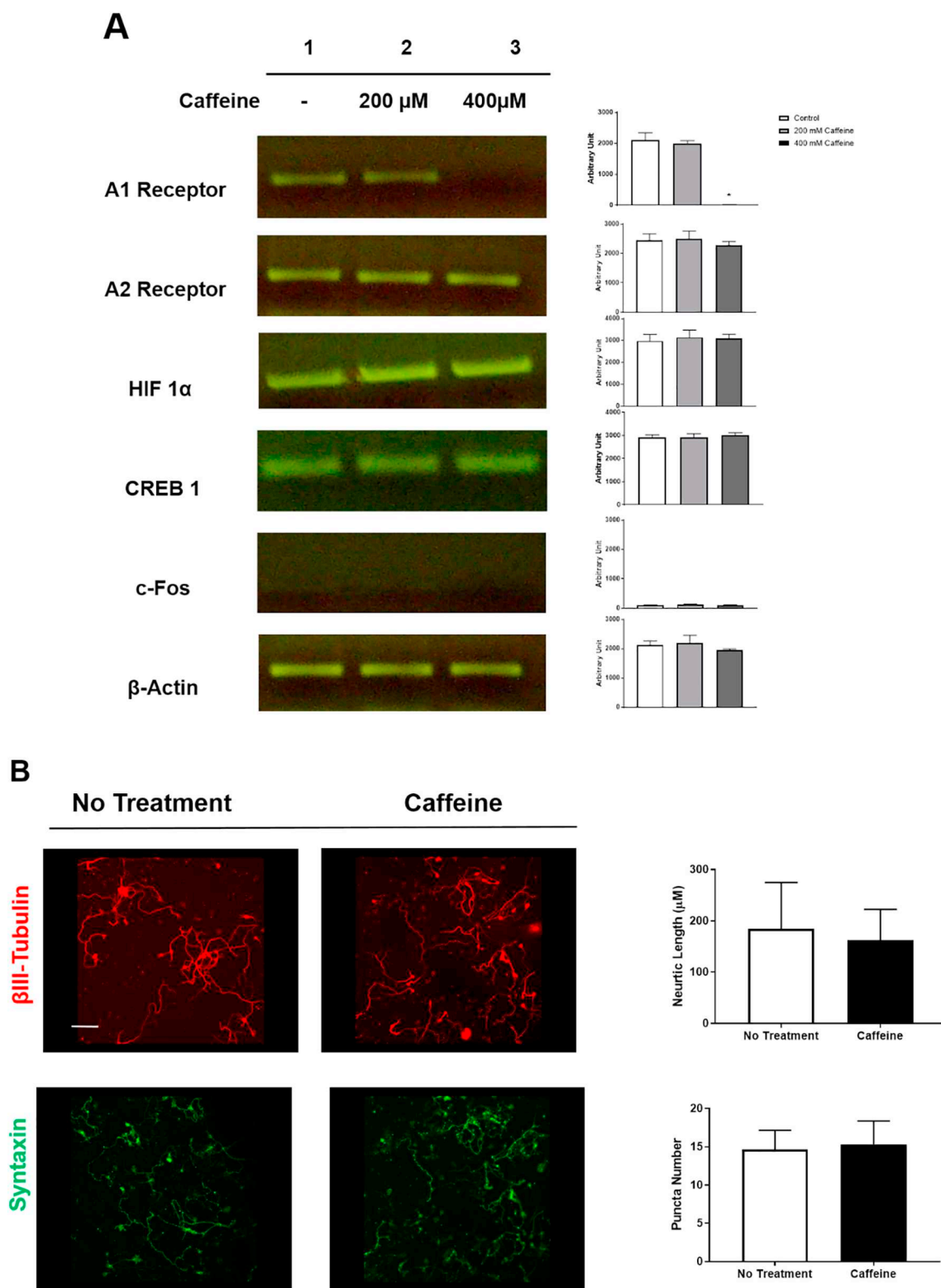


Fig. 2. (A) Treatment with 200 μ M caffeine has minimal/no effect on the transcription of A₁R and A₂R, HIF-1 α , CREB-1 or c-Fos *in vitro*. Single cell RT/PCR was performed on neuronal culture that were treated with or without caffeine for 5 days (n = 10). The intensities of the RT-PCR bands were quantified by densitometry in arbitrary units. The results of control and caffeine groups are as follows: A₁R (2104 $\pm$ 138, 2000 $\pm$ 136), A₂R (2446 $\pm$ 130, 2500 $\pm$ 150), HIF-1 α (2978 $\pm$ 17.5, 3141 $\pm$ 19.3), CREB-1 (2928 $\pm$ 64, 2933 $\pm$ 88) and c-Fos (105 $\pm$ 7.5, 132 $\pm$ 7.6). The levels of β -actin were used as a loading control. The transcription levels of CREB-1 and HIF-1 α were discernible, but the level of c-Fos was barely detectable. A high dose of caffeine (400 μ M) selectively decreased the transcription of A₁R (36 $\pm$ 0.3, p < 0.001) but not other tested factors. (B) Treatment with 200 μ M caffeine did not affect neurite length (beta-III tubulin, red) (184.9 $\pm$ 27.16 μ m for control and 162.1 $\pm$ 17.45 μ m for caffeine treatment group) and synapse formation (syntaxin, green) (14.67 $\pm$ 1.45 for control and 15.33 $\pm$ 1.76 for caffeine treatment group). The quantitative results are shown on the right. Scale bar, 100 μ m (n = 5). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

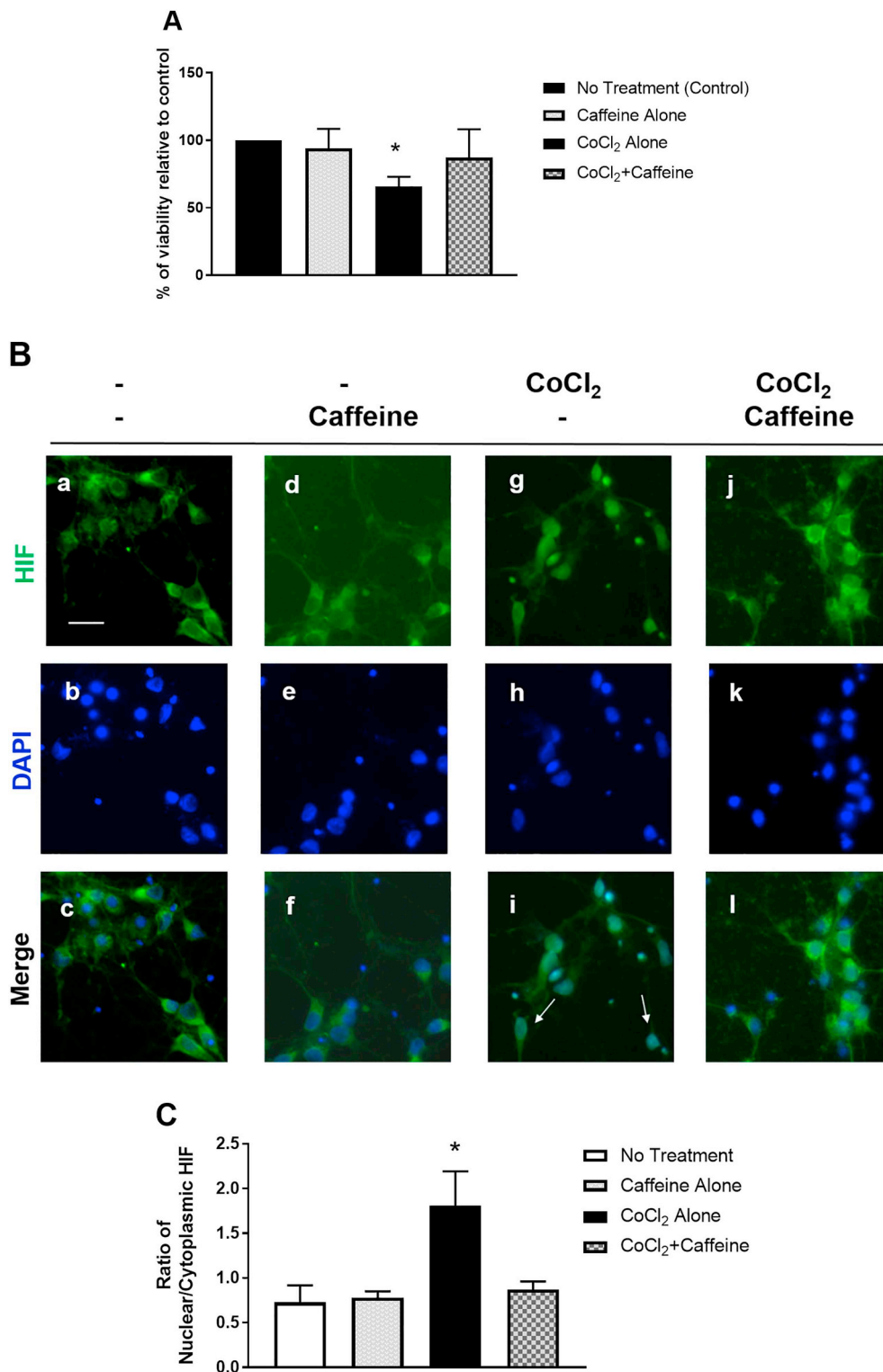


Fig. 3. Caffeine promoted cell survival after hypoxia and decreased CoCl₂-induced nuclear accumulation of HIF-1α *in vitro*. (A) Primary cortical neuronal cultures were treated with CoCl₂ or vehicle (control) for 24 h. Each group was divided into two subgroups that were either treated with 100 μM caffeine or vehicle for an additional 24 h. The viability of each treatment group was subsequently measured by MTT assays. Data are presented as percentage of viability in each group relative to that of the control group (control, 100%; caffeine alone, 94 ± 7.1%; CoCl₂ treatment, 65.6 ± 3.6%; CoCl₂ + caffeine, 87.2 ± 10.5% n = 4. *p* < 0.001). (B) Treated neurons were double-immunostained to label HIF-1α (green, top row) and neuron-specific beta-III tubulin (red, not shown) and counter-stained with DAPI for nuclei (blue, middle row). The merged images of HIF-1α and DAPI are shown in the bottom row. Beta-III tubulin immunostaining (not shown) was used as a neuronal marker. In the absence of CoCl₂, HIF-1α was primarily localized in the cytoplasm regardless of whether neurons received caffeine or not (Lane 1, a, b, c and Lane 2, d, e, f). In contrast, CoCl₂ triggered nuclear co-localization of HIF-1α with DAPI (Lane 3, g, h, i), suggesting nuclear accumulation of HIF-1α. White arrows indicate co-localization of HIF-1α and DAPI. This nuclear accumulation of HIF-1α was alleviated by subsequent treatment with caffeine (Lane 4, j, k, l). Scale bar, 20 μm. (C) Quantification of the ratio of nuclear vs cytoplasmic HIF-1α in neurons of each treatment group (control, 0.73 ± 0.07; caffeine alone, 0.78 ± 0.03; CoCl₂ treatment, 1.81 ± 0.17, CoCl₂ and caffeine, 0.82 ± 0.04, *p* < 0.001, n = 5). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

syntaxin puncta (15.33 ± 1.76) in neurons that were treated with 200 μM caffeine for 5 days is comparable to that of the untreated neurons ($184.9 \pm 27.6 \mu\text{m}$ and 14.67 ± 1.45 , respectively) (Fig. 2B). Together, our data defined the safety threshold for caffeine at 200 μM since this dose did not perturb basic neuronal functions and characteristics *in vitro*.

We next sought to determine whether caffeine treatment promotes neuronal survival after hypoxic ischemia. Many of the cellular responses induced by hypoxia are mediated by changes in gene

expression, which are often regulated by HIF-1α (Ke and Costa, 2006; Semenza, 2007; Shi, 2009). Under normal conditions, HIF-1α is constitutively degraded by prolyl-hydroxylase enzymes. However, hypoxia stabilizes HIF-1α by inhibiting these enzymes. Cobalt chloride (CoCl₂) is a hypoxia mimetic agent *in vitro* since it also inhibits prolyl-hydroxylase enzymes, resulting in accumulation and nuclear translocation of HIF-1α (Li et al., 2015; Piret et al., 2002). Here, we used CoCl₂ to mimic hypoxia *in vitro*. Primary neurons (5–7 days in culture) were treated with 50–125 μM CoCl₂ for 24 h as previously described (Wu and

Yotnda, 2011). The culture medium was discarded and replenished with conditioned medium in the presence or absence of 100 μ M caffeine for an additional 24 h. Subsequently, cells were subjected to MTT assay to measure cell survival rate (Denizot and Lang, 1986). In this experiment, the MTT reading of control group (no treatment) was defined as 100% viability. The MTT readings of other groups were compared with that of the control group, and the percentage of viability was derived accordingly. We found that the viability of neuronal cultures was comparable in the presence or absence of caffeine (Fig. 3A; control, 100%; caffeine alone, $94 \pm 7.1\%$), suggesting caffeine does not affect baseline cell survival. As expected, CoCl_2 decreased the viability of neuronal cultures compared to that of untreated cultures (Fig. 3A; CoCl_2 treatment, $65.6 \pm 3.6\%$, $p < 0.001$). Interestingly, the low viability caused by CoCl_2 was alleviated significantly by subsequent treatment with 100 μ M caffeine (Fig. 3A; CoCl_2 + caffeine, $87.2 \pm 10.5\%$, $n = 4$, $p < 0.001$).

HIF-1 α appears to have complex effects in hypoxic brains in a time-dependent manner (Supplementary Table S1). Accumulation of HIF-1 α after ischemia has been shown to facilitate cell death at the very early phase (< 24 h, pro-death effect) (Bartczek et al., 2017; Cheng et al., 2014; Yang et al., 2017), but HIF-1 α has also been shown to limit infarct size at a later stage (> 4 d, pro-survival effect) (Baranova et al., 2007; Bergeron et al., 2000; Sheldon et al., 2009, 2014). Since caffeine treatment increased neuronal viability immediately after hypoxia, we hypothesized that caffeine could decrease the accumulation of HIF-1 α , therefore inhibiting its pro-death effect. To test this hypothesis, neuronal cultures were treated as in Fig. 3A. We then co-immunostained the neuronal culture with 1) antibody against beta-III tubulin for neuronal labeling, 2) antibody against HIF-1 α transcription factor and 3) DAPI for nuclear staining. The ratio of the pixel intensity of HIF-1 α immunostaining in the nucleus vs cytoplasm of the neurons was computed using Image J. Prior to the induction of hypoxia, the ratio of nuclear vs cytoplasmic HIF-1 α is comparable in cultures treated with 100 μ M caffeine or vehicle (0.78 ± 0.03 and 0.73 ± 0.07 , respectively) (Fig. 3B and C, Lane 1 and 2), suggesting that caffeine alone did not affect nuclear levels of HIF-1 α . However, this ratio increased significantly in CoCl_2 -treated cultures (1.81 ± 0.17 , $p < 0.001$) compared to that of untreated cultures, suggesting nuclear accumulation of HIF-1 α in CoCl_2 -induced hypoxia (Fig. 3B and C). For most of the study, we used 125 μ M CoCl_2 since this concentration triggered a significant nuclear accumulation of HIF-1 α and cell death (Fig. 3B and C). Interestingly, subsequent treatment with 100 μ M of caffeine alleviated this hypoxia-induced nuclear accumulation of HIF-1 α (0.82 ± 0.04 , $p < 0.001$) (Fig. 3B and C).

3.3. Caffeine suppresses hypoxia-induced nuclear accumulation of HIF-1 α factor *in vivo*

We next sought to examine whether caffeine treatment in newborn mice is neuroprotective for subsequent hypoxia exposure. Here, caffeine was given to neonatal pups before induction of hypoxia in order to 1) avoid the high mortality rate when carotid ligation is performed in newborn mice at the age of P0–P4, and 2) avoid the injury-induced plasticity obscuring the potential effects of caffeine on neuroprotection and 3) mimic the timing of caffeine therapy in preterm infants.

Neonatal pups were gavage fed with caffeine as previously described (Gaytan et al., 2006). After caffeine treatment, the animals were exposed to a hypoxic or normoxic environment for 20 min before euthanization (Zaghloul et al., 2014). Their brains were removed immediately after the procedure and the brain sections were immunostained with HIF-1 α antibody and counter stained with DAPI.

We first ensured caffeine treatment did not perturb basic neuronal functions. We found that the expression and subcellular localization of A₁R in various brain areas were similar whether neonatal pups received caffeine or not (Fig. 4A, the puncta number in cortex is 70 ± 1.15 in control group and 67.3 ± 1.86 in caffeine group). Caffeine treatment

also did not affect the punctate pattern of A₁R in cerebellum and brain stem (data not shown). In addition, we did not observe any significant changes in immunostaining for AMPA receptors, CREB-1 and c-Fos in the brains of neonatal rodents that were treated with vehicle or caffeine (AMPA puncta, 67.6 ± 2 and 63.6 ± 2 ; CREB-1, 79 ± 2.1 , 81.3 ± 1.5 ; c-Fos, 1 ± 0.58 , 1 ± 0.1 , respectively) (Fig. 4A; an enlarged image of AMPA receptor puncta is in Supplementary Fig. S3). Together, these data suggested that this clinically relevant dose of caffeine did not have a discernible impact on A₁R expression and the protein levels of AMPAR, CREB-1, and c-Fos.

Under normoxia, caffeine treatment did not affect the ratio of nuclear vs cytoplasmic HIF-1 α in the brain of P7 pups whether the animals received caffeine or not (0.71 ± 0.05 for control group and 0.77 ± 0.03 for caffeine treatment group) (Fig. 4B and C, Lane 1 and 2). Hypoxia increased the ratio of nuclear vs cytoplasmic HIF-1 α in P7 pups that did not receive caffeine therapy (1.33 ± 0.05 , $p < .001$) (Fig. 4B and C, Lane 3). In contrast, the same hypoxic condition failed to trigger a significant nuclear accumulation of HIF-1 α in neonatal pups that had received caffeine feeding previously (the ratio of nuclear vs cytoplasmic HIF-1 α is 0.9 ± 0.02 , $p < .001$) (Fig. 4B and C, Lane 4), suggesting a prophylactic effect of caffeine in preventing upregulation in HIF-1 α by subsequent hypoxia.

4. Discussion

Caffeine therapy is widely used to treat AOP because of its effectiveness and safety. Caffeine relieves AOP by competing with adenosine for binding to its receptors, A₁R and A_{2A}R, in brain stem. However, the effects of caffeine at this high dose on neonatal brains remained unclear. In this study, we first showed that the neonatal brain of both rodents and preterm infants expressed A₁R and that this receptor was enriched in synapses. In addition, we also detected A_{2A}R mRNA by single cell RT/PCR in primary neuronal cultures. These data suggested that neonatal brains could be responsive to caffeine via A₁R and potentially A_{2A}R. We then showed that caffeine was considered safe in neonatal neurons since it did not perturb several basic neuronal functions, including the expression and distribution of A₁R, transcription of CREB-1, c-Fos and HIF-1 α and neurite outgrowth and synapse formation. Lastly, we determined the beneficial effects of caffeine in alleviating hypoxia-induced neuronal death. We found that caffeine at clinically relevant doses suppressed hypoxia-induced nuclear accumulation of HIF-1 α both *in vitro* and *in vivo*, and promoted viability in neuronal cultures exposed to hypoxia.

4.1. A₁R is synaptically localized in neonatal brains

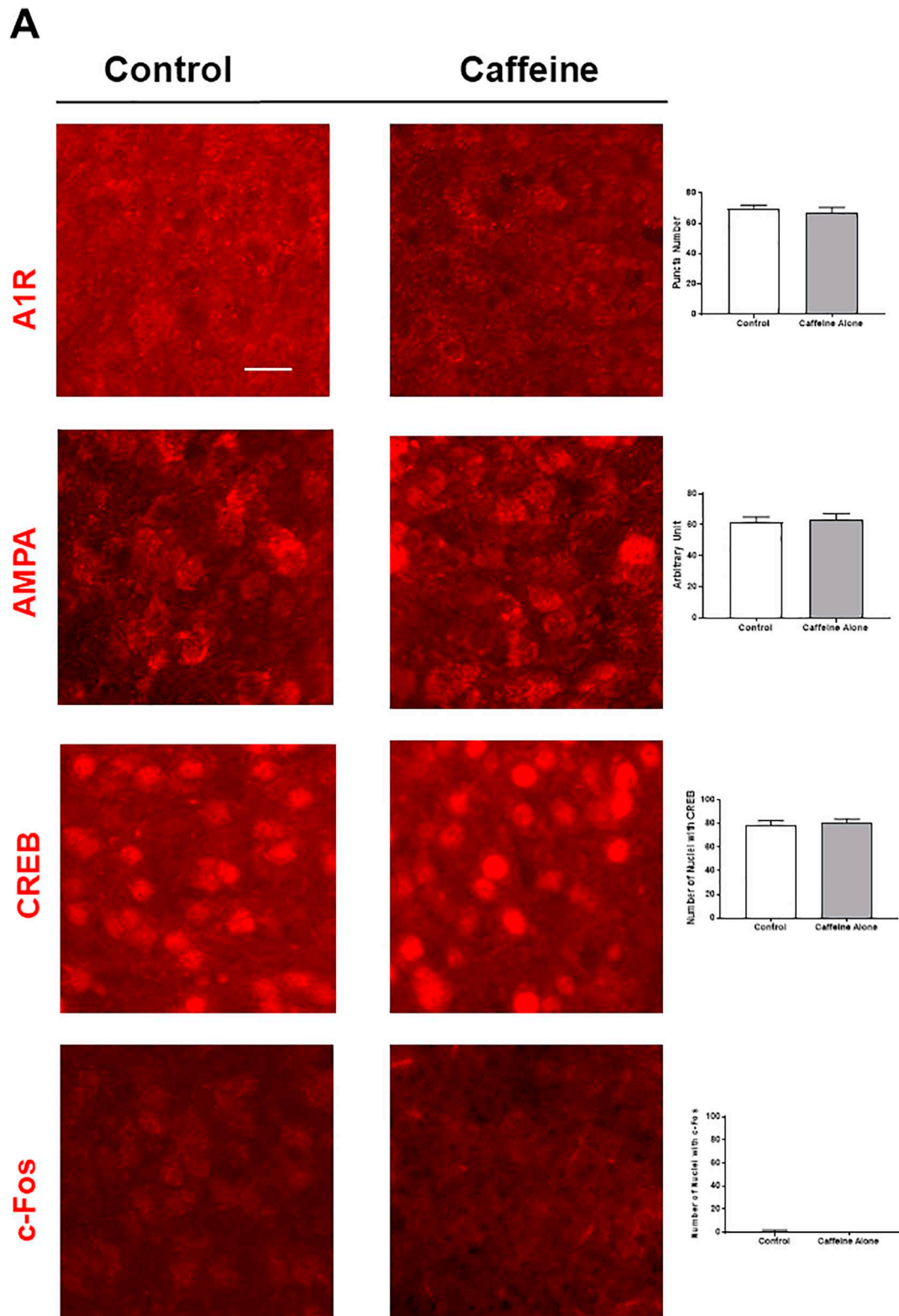
The major receptors for caffeine are adenosine A₁R and A_{2A}R (Aden et al., 2000; Fredholm, 1995). However, the protein expression and subcellular localization of these receptors in developing neurons remain unclear. We found that the brains of neonatal mice and deceased preterm infants expressed A₁R in brain areas, such as cortex, basal ganglia, thalamus, and hippocampus. We also found A₁R was enriched in synapses. The synaptic targeting of A₁R began at neonatal stages, albeit to a lesser extent, since the A₁R puncta became more prominent as the mouse pups matured into adulthood (Fig. 1B). Interestingly, the synaptic targeting of A₁R is functionally linked to its neuromodulatory role in the adult brain (Rebola et al., 2003; Sheth et al., 2014).

In contrast to A₁R, we found A_{2A}R mRNA by single cell RT/PCR was expressed in neonatal neuronal culture, but the protein distribution of A_{2A}R in neonatal brains remained unclear. Previous reports showed soma enrichment of A_{2A}R in the respiratory nuclei of neonatal brain stem (Gaytan and Pasaro, 2012). We also observed soma/nuclear enrichment of A_{2A}R by immunostaining, but unfortunately, this strong immunostaining was present in both wild type brains and A_{2A}R

deficient brains, rendering inconclusive results (Fig. 1A). As a control, we also tested these antibodies in adult brains since radio-ligand binding assays have clearly shown that the expression of A_{2A}R is more enriched in striatum and olfactory bulb in adult brains (Fredholm et al., 2011), but none of these commercial antibodies showed this immunostaining pattern in adult brains.

4.2. Clinically relevant doses of caffeine had minor/no effects on synapse formation and expression of A₁R, CREB-1 and c-Fos

Caffeine has been shown to regulate the synaptic functions in adult cortical regions in several *in vitro* experiments (Greene et al., 1985; Yoshimura, 2005). However, we did not observe any differences in neurite length, synaptic density or the expression of several



(caption on next page)

Fig. 4. Caffeine blocked hypoxia-induced nuclear accumulation of HIF1- α *in vivo*. (A) Immunostaining for A1R, AMPA receptors, CREB-1 and c-Fos showed that caffeine treatment has minimal/no effect on the expression of these factors in neonatal cortex ($n = 5$). Scale bar, 20 μm . The quantitative results in control and caffeine-treated groups are shown on the right; the number of A₁R (70 ± 1.15 , 67.3 ± 1.86) or AMPA receptor puncta (67.6 ± 2 , 63.6 ± 2), the number of nuclear CREB-1 (79 ± 2.1 , 81.3 ± 1.5) or c-Fos (1 ± 0.58 , 1 ± 0.01). (B) Neonatal mouse pups were gavage fed with caffeine or vehicle from P4-P7. Subsequently, pups were placed under normoxic (room air) or hypoxic (8% O₂) conditions for 20 min prior to cardiac perfusion and isolation of their brains. Brain sections were immunostained with anti-HIF-1 α (green, top row) and counter-stained with DAPI to show nuclei (blue, middle row). The overlaid images of HIF-1 α immunostaining and DAPI staining are shown in the bottom row. Representative cortical images are shown here. Under normoxic conditions, HIF-1 α primarily distributed in the cytoplasm of cortical neurons whether mouse pups received caffeine therapy or not (Lane 1, a, b, c. and Lane 2, d, e, f). In pups without caffeine therapy, hypoxia induced nuclear accumulation of HIF-1 α (Lane 3, g, h, i). White arrows indicate co-localization of HIF-1 α and DAPI. Pre-treatment with caffeine prevented subsequent hypoxia-induced nuclear accumulation of HIF-1 α in neonatal cortex (Lane 4, j, k, l). Scale bar, 20 μm . (C) Quantification of the ratio of nuclear vs cytoplasmic HIF-1 α in neonatal cortex in each group (control, 0.71 ± 0.05 ; caffeine alone, 0.77 ± 0.03 ; hypoxia, 1.33 ± 0.05 ; hypoxia and caffeine, 0.9 ± 0.02 , $p < 0.001$, $n = 5$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

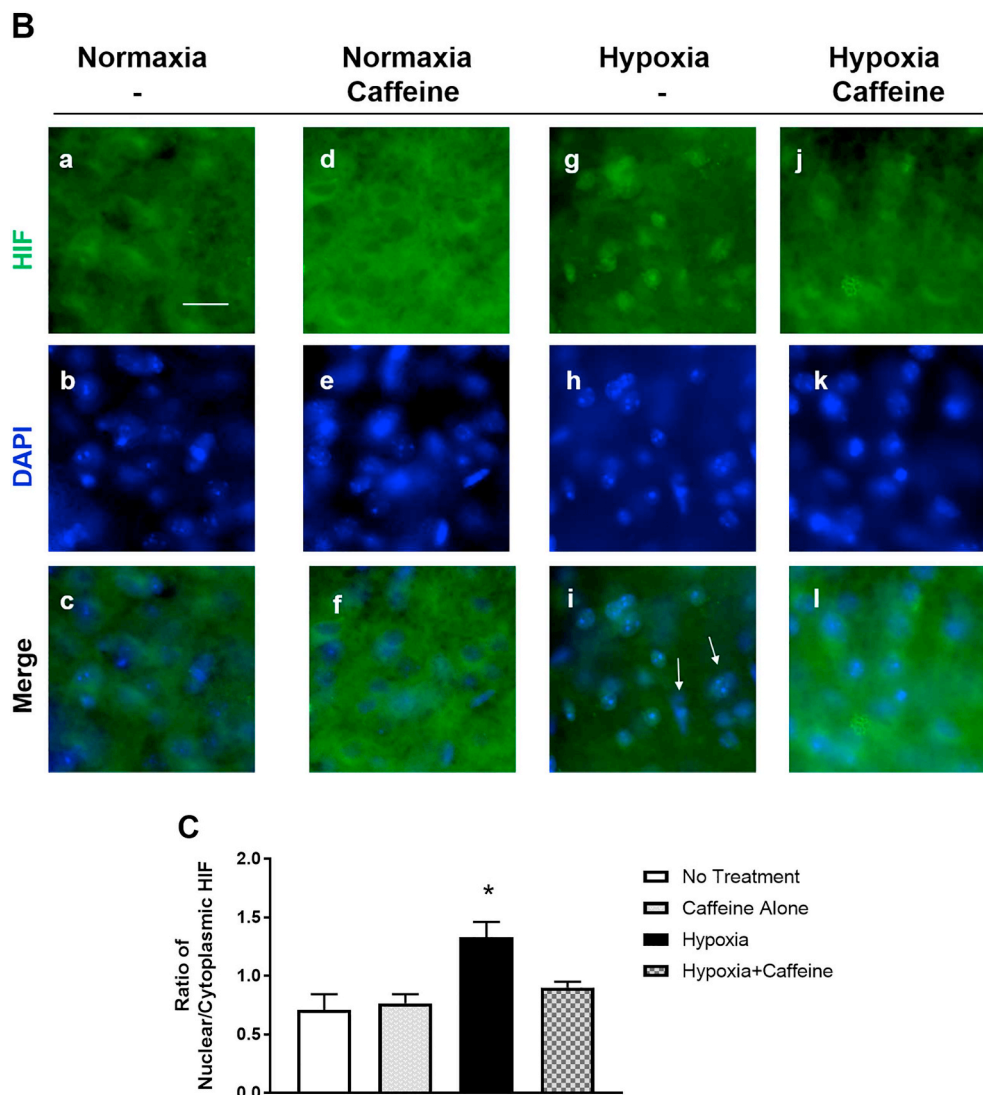


Fig. 4. (continued)

transcription factors between caffeine-treated and untreated neonatal neuronal culture. Moreover, under normoxic condition, the morphology of neonatal brains from pups receiving caffeine treatment appeared similar to that from untreated group.

A previous study has shown that caffeine increased A₁R transcription in the brain stem and the respiratory nuclei of the hypothalamus when caffeine was given to neonatal pups directly (Gaytan and Pasaro, 2012). The same study also demonstrated a caffeine-induced early shift of the postnatal increase in c-Fos in these regions. However, in our study, we did not observe any changes in 1) the protein levels of A₁R in

the neonatal cortex and other regions (hippocampus/medulla/cerebellum/thalamus), and 2) the transcription levels of A₁R in neuronal cultures. We also found that the protein levels of c-Fos were low in both control and caffeine-treated groups. Since we also fed neonatal pups with caffeine directly or added caffeine into neuronal cultures directly, this discrepancy may arise from analyzing different brain regions and using different methodology. For example, we used single cell RT-PCR to analyze pure neuronal population, whereas Gaytan and colleagues used qPCR to analyze the whole extracts of hypothalamus and respiratory nuclei.

4.3. Caffeine blocks hypoxia-induced nuclear accumulation in HIF-1 α and promotes neuronal survival

It has been suggested that caffeine has opposite effects on embryonic vs neonatal brains because caffeine is a potent inhibitor of A₁R. During the embryonic stage, inhibition of A₁R rendered cells more susceptible to hypoxia, whereas inhibition of A₁R in neonatal brains after birth was neuroprotective in white matter injury and hypoxic ischemia in rodents (Rivkees and Wendler, 2011). Notably, caffeine therapy for AOP and most related research in neonatal rodents employed postnatal treatment. Thus, caffeine has been suggested to have neuroprotective effects during the neonatal period (Back et al., 2006; Cunha, 2001; Ferreira and Paes-de-Carvalho, 2001; Fredholm et al., 2011; Rivkees and Wendler, 2011; Winerdal et al., 2017) and are beneficial to neurodevelopment in preterm infants (Murner-Lavanchy et al., 2018; Schmidt et al., 2007).

Here, we showed a novel mechanism by which caffeine exerts its neuroprotective effects in neonatal brains. Hypoxia generally results in tissue damage immediately after ischemia. The “pro-death” effect of HIF-1 at this stage has been shown to facilitate death of severely injured neurons (Supplementary Table S1) (Bartczek et al., 2017; Cheng et al., 2014; Liu et al., 2015; Yang et al., 2017). We found that caffeine alleviated hypoxia-induced accumulation of HIF-1 α both *in vivo* and *in vitro* and therefore increased the viability of primary neurons. This inhibitory effect is specific to nuclear accumulation of HIF-1 α , not on its transcription (Supplementary Fig. S2). In addition, caffeine had neuroprotective effects *in vivo* whether caffeine was administered before or after hypoxic insults. A recent study showed that a single dose of caffeine (5 mg/ml *via* intraperitoneal injection) immediately after neonatal hypoxic ischemia in neonatal pups decreased brain atrophy and improved behavioral outcomes at 2 weeks after hypoxic insults (Winerdal et al., 2017). However, in our study, caffeine was given to neonatal pups (P4–P7) before induction of mild hypoxia (8% O₂ in 20 min). We found that early caffeine therapy could prevent subsequent hypoxia-induced accumulation of HIF-1 α . Clinically, our data suggest that caffeine therapy in the NICU may protect preterm brains from hypoxic damages that may occur during their NICU stay.

In conclusion, our results further support the utility of caffeine in preventing hypoxia-induced nuclear accumulation of HIF-1 α and promotes neuronal survival.

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Conflict of interest

All authors have read the journal's policy on disclosure of potential conflicts of interest and have none to declare. This study was supported by two non-profit foundations. The funders played no role in the design and conclusion of this study.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.expneurol.2019.01.014>.

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