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Hypoxic preconditioning protects human brain endothelium from ischemic apoptosis by Akt-dependent survivin activation

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Hypoxic preconditioning protects human brain endothelium from ischemic apoptosis by Akt-dependent survivin activation. Am J Physiol Heart Circ Physiol 292: H2573–H2581, 2007. First published March 2, 2007; doi:10.1152/ajpheart.01098.2006.—Preconditioning-induced ischemic tolerance is well documented in the brain, but cell-specific responses and mechanisms require further elucidation. The aim of this study was to develop an in vitro model of ischemic-tolerance in human brain microvascular endothelial cells (HBMECs) and to examine the roles of phosphatidylinositol 3-kinase (PI3-kinase)/Akt and the inhibitor-of-apoptosis protein, survivin, in the ability of hypoxic preconditioning (HP) to protect endothelium from apoptotic cell death. Cultured HBMECs were subjected to HP, followed 16 h later by complete oxygen and glucose deprivation (OGD) for 8 h; cell viability was quantified at 20 h of reoxygenation (RO) by the 3-(4,5-dimethylthiazol-2,5-diphenyltetrazolium bromide assay. HBMECs were examined at various times after HP or OGD/RO using immunoblotting and confocal laser scanning immunofluorescence microscopy for appearance of apoptotic markers and expression of phosphorylated (p)-Akt and p-survivin. Causal evidence for the participation of the PI3-kinase/Akt pathway in HP-induced protection and p-survivin upregulation was assessed by the PI3-kinase inhibitor LY-294002. HP significantly reduced OGD/RO-induced injury by 50% and also significantly reduced the OGD-induced translocation of apoptosis-inducing factor (AIF) from mitochondria to nucleus and the concomitant cleavage of poly(ADP-ribose) polymerase-1 (PARP-1). PI3-kinase inhibition blocked HP-induced increases in Akt phosphorylation, reversed the effects of HP on OGD-induced AIF translocation and PARP-1 cleavage, blocked HP-induced survivin phosphorylation, and ultimately attenuated HP-induced protection of HBMECs from OGD. Thus HP promotes an antiapoptotic phenotype in HBMECs, in part by activating survivin via the PI3-kinase/Akt pathway. Survivin and other phosphorylation products of p-Akt may be therapeutic targets to protect cerebrovascular endothelium from apoptotic injury following cerebral ischemia.

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thelium and to begin to elucidate the mechanistic basis for such apoptotic resistance. We tested the hypothesis that the PI3-kinase/Akt pathway participates in establishing the ischemia-tolerant phenotype following HP and that p-Akt-mediated phosphorylation of the IAP protein survivin is one antiapoptotic effector mediating protection of cerebral endothelium against ischemia-reperfusion injury.

METHODS

Cerebral endothelial cell culture. Human brain microvascular endothelial cells (HBMECs) (13) were a generous gift from Dr. Sean P. Colgan (Harvard Medical School) and cultured on 0.1% collagen I-coated dishes or plates, as described previously (61). Cell purity was assessed by periodic immunostaining for prototypical endothelial- and glial-specific markers and routinely examined for the prototypical cobblestone appearance under phase; similar validation studies were performed in a previous study, as well as uptake of fluorescent-acetylated LDL (13).

HP protocol. Because the preconditioning OGD recovery protocol we adopted spanned 5 days in total, we initiated 3 consecutive days of HP when HBMECs were at 70% confluence, as follows: after being washed three times, cultures were transferred to a 37°C incubator within a hypoxic chamber (93% nitrogen-5% CO2-2% oxygen), and HBSS media were replaced with medium 199 (M199; without serum) that was prebubbled for 5 min with the same gas mix to provide a media PO2 (14.7 mmHg) equivalent to that in the ambient air of the chamber. This first exposure to hypoxia lasted 3 h, followed by a 1-h period of normoxia (21% oxygen-5% CO2-74% nitrogen), after which they were returned to the chamber and given fresh hypoxic media for a second 3-h hypoxia exposure. With each return to normoxia, oxygenated complete M199 containing 20% serum was added. Three consecutive days of these same paired 3-h hypoxic exposures constituted the HP stimulus. Measures of p-Akt and p-survivin were obtained 1 h following the last day of the preconditioning stimulus, at a time coinciding with the initiation of OGD.

In some experiments, LY-294002 (Sigma, St. Louis, MO), a PI3-kinase inhibitor, was added to the experimental groups at a concentration of 10 μmol/l, was more effective in blocking the protective effects of HP than 10 μmol/l (with 5 μmol/l being ineffective), and there was a slight cytotoxicity from a 50-μmol/l dose. We did not conduct activity assays for PI3-kinase following LY-294002, but we did measure p-Akt levels after LY-294002 administration by immunoblotting to document its effect.

OGD and reoxygenation, and cell viability determinations. Cells with or without previous HP treatment were subjected to an 8-h period of lethal OGD/reoxygenation (RO) starting 16 h after the last HP stimulus as described in detail in an earlier publication (61). In brief, OGD was induced by placing the cells in a 37°C incubator housed within an anoxic chamber (95% nitrogen-5% CO2) and replacing the media with HBSS (without serum) that was bubbled for at least 5 min with the same gas mix; measurements of media PO2 (3.7 mmHg) revealed a level of near complete anoxia (<0.5% oxygen) that was identical to that measured in the ambient air of the chamber. RO was undertaken at 37°C by providing the cells media (M199) with 1% serum and normoxic conditions (21% oxygen-5% CO2-74% nitrogen). At 4 h of RO, poly(ADP-ribose) polymerase (PARP) cleavage and apoptosis-inducing factor (AIF) translocation were determined by immunoblotting; at 20 h of RO, HBMEC viability was quantified by a reduction of 3-(4,5-dimethylthiazol)-2,5-diphenyltetrazolium bromide, as described previously (61).

Laser scanning confocal immunofluorescence microscopy. For laser confocal immunofluorescence microscopy of p-Akt, von Willebrand Factor, glucose transporter-1 (Glut-1), glial fibrillary acidic protein (GFAP), cleaved PARP-1, AIF, and the inhibitor of apoptosis family protein survivin, HBMECs were seeded on round glass coverslips (BD Biosciences, San Diego, CA) coated with 1% collagen-I in six-well plates. At appropriate time points after different treatments, medium was removed, cells were washed and fixed with 4% paraformaldehyde for 10 min and then permeabilized and blocked for 1 h at room temperature in PBS containing 5% normal serum and 0.3% Triton X-100. Cells were incubated overnight at 4°C in blocking buffer containing 1:200 rabbit anti-human p-Akt (Cell Signaling Technology, Beverly, MA), 1:200 mouse anti-human von Willebrand factor antibody (Lab Vision, Fremont, CA), 1:200 mouse anti-human Glut-1 antibody (a gift from Dr. William R. Frazier, Dept. of Biochemistry, Washington Univ., St. Louis, MO), 1:200 mouse anti-human GFAP antibody (a gift of Belinda McMahan, Dept. of Ophthalmology, Washington Univ.), mouse anti-human cleaved PARP-1 antibody (1:200; Cell Signaling Technology), rabbit anti-human AIF antibody (1:200; Chemicon International, Temecula, CA), rabbit anti-p-Akt antibody, and human p-survivin antibody (Thr34) (1:50; Santa Cruz, Santa Cruz, CA), followed by fluorescein Alexa-560-conjugated anti-mouse or anti-rabbit IgG (1:500) (Molecular Probes, Eugene, OR) for 1 h at room temperature. Nuclear DNA was stained with 4’,6-diamidino-2-phenylindole. The specimens were observed at x40 under a laser-scanning confocal microscope (Carl Zeiss, LSM 5 PASCAL) at the excitation wavelength of 405 and 560 nm. To distinguish the colors, especially the merge color easily, the original colors of blue for nucleus and red for proteins were adjusted to red and green, respectively.

Subfractions and immunoblotting. For PARP-1 cleavage and AIF translocation, HBMECs were collected at 4 h of normoxic RO after OGD (with and without prior HP), and nuclear extracts were obtained (61). In brief, cells were washed with ice-cold PBS, scraped from dishes, and centrifuged (600 g for 5 min); the pellet was then resuspended in lysis buffer containing (in mM) 20 HEPESS-KOH (pH 7.4), 10 NaCl, 1.5 MgCl2, 1 EDTA, 1 EGTA, and 250 sucrose and 1× protease inhibitor cocktail. Following centrifugation (600 g for 10 min), the supernatant was discarded and the pellet was washed and resuspended in nuclear extraction buffer [containing (in mM) 20 Tris-HCl (pH 7.5), 1.5 MgCl2, 420 NaCl, and 0.2 EDTA and 25% glycerol, 0.5% Triton X-100, 0.1% Nonidet P-40, and 1× protease inhibitor cocktail], vortexed, and shaken for 30 min. The suspension was then centrifuged (14,000 g for 10 min), and the supernatant, which contained the nuclear fraction, was transferred to a prechilled microcentrifuge tube. The primary antibodies used to probe the blots overnight at 4°C were a mouse anti-human-cleaved PARP-1 antibody (1:100; Cell Signaling Technology) and a rabbit anti-human AIF antibody (1:2,000; Chemicon International). p-Akt and p-survivin immunoblotting was performed on whole cell lysates, obtained 16 h after the last preconditioning stimulus at the time when sister cultures were exposed to OGD. Blots were probed overnight at 4°C with a rabbit anti-human p-Akt (for phosphorylation at Ser473; 1:1,000; Cell Signaling Technology) and a rabbit anti-human AIF antibody (1:2,000; Chemicon International), p-Akt and p-survivin immunoblots were performed on whole cell lysates, obtained 16 h after the last preconditioning stimulus at the time when sister cultures were exposed to OGD. Blots were probed overnight at 4°C with a rabbit anti-human p-Akt (for phosphorylation at Ser473; 1:1,000; Cell Signaling Technology) and a rabbit anti-human p-survivin antibody (1:500; Santa Cruz). For all blots, incubations with horseradish peroxidase-conjugated secondary antibodies were followed by detection of immunoreactive proteins using enhanced chemiluminescence (Cell Signaling Technology). After being scanned, protein bands were quantified with ImagePro Plus software and standardized for statistical analysis.

Statistics. All results are presented as means ± SE. For single and multiple comparisons among the experimental groups, Mann-Whitney nonparametric rank sum tests or ANOVA on rank tests, respectively, were used to calculate significance. In each case, significance was defined as P < 0.05.

RESULTS

Phenotypic confirmation. HBMECs exhibited the characteristic “cobblestone” appearance of confluent endothelial cells

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HP improves HBMEC viability following simulated ischemia. We assessed the effects of different durations of HP on cellular viability to an 8-h OGD insult that caused a moderate level of injury (39% cell death) in untreated HBMECs; improvements in cell viability at 20 h of RO were dependent on the duration of HP and whether hypoxia was continuous or intermittent (Fig. 2). Significant, but modest, cytoprotection (29 ± 1% cell death; 26% protection) was achieved by 3 consecutive days of 4 h of continuous HP. Increasing the duration of HP to 6 h reduced cell death to 26 ± 3% (33% protection). However, exposing HBMECs to the same 6 h of hypoxia in two 3-h episodes (separated by 1 h of normoxia) reduced OGD/RO-induced cell death to 19 ± 3% (51% protection). We adopted this HP protocol (3 h + 3 h) for the rest of the experiments reported herein. The preconditioning itself did not cause any noticeable cell injury in terms of cell viability loss and apoptotic marker appearance (data not shown).

HP reduces OGD-induced apoptosis of HBMECs. By subcellular fractionation analysis, we reconfirmed our earlier finding (61) that apoptosis, reflected by a significant increase in nuclear AIF expression (Fig. 3, A and C), that HP significantly reduces these two apoptotic indexes. The HP-induced inhibition of AIF translocation (Fig. 3B) and PARP cleavage (Fig. 3D) was also evident by confocal microscopy. In response to its predominantly nonnuclear location under baseline conditions, AIF can be observed to redistribute to the nucleus following OGD (Fig. 3B, top and middle). HP prior to OGD attenuated this translocation, as reflected by reduced nuclear AIF expression (Fig. 3D, bottom). With respect to PARP, confocal microscopy imaging with an antibody specific for cleaved PARP reveals an obvious increase in nuclear PARP cleavage following OGD and the ability of prior HP to attenuate this cleavage event (Fig. 3D). Together, these results indicate that HP-induced improvements in cell viability following OGD/RO (Fig. 2) are the result of a reduction in apoptotic cell death.

HP increases PI3-kinase/Akt pathway signaling. Since the PI3-kinase/Akt survival pathway has been implicated in the antiapoptotic effect of a variety of interventions in endothelial (36, 48, 62) and other cells (26, 49, 51), we examined whether HP affects levels of p-Akt in our HBMEC model. Sixteen hours after the last HP treatment, at a time just before when the cells would be subjected to OGD, we found a threefold increase in p-Akt levels (Fig. 4A), which was revealed by confocal fluorescence microscopy to be primarily cytosolic (Fig. 4B). The addition of the PI3-kinase inhibitor LY-294002 during HP effectively blocked the HP-induced increase in Akt phosphorylation (Fig. 4, A and B). At the concentration we used in the current study, no noticeable toxicity of LY-294002 was observed. Moreover, this pharmacological intervention reversed the effects of HP on OGD-induced nuclear AIF translocation and cleavage of nuclear PARP-1, as evidenced by immunoblotting (Fig. 5A) and confocal microscopy (data not shown) and, in turn, blocked HP-induced HBMEC cytoprotection (Fig. 5B). Thus increased p-Akt levels appear critical to the HBMEC protection afforded by HP, secondary to reductions in AIF translocation and PARP-1 cleavage.

Survivin is a phosphorylation target of p-Akt. To begin to address the downstream targets of p-Akt involved in mediating HP-induced antiapoptotic protection, we measured changes in p-survivin protein levels following HP. As shown in the immunoblotting in Fig. 6A, we found that HP led to significant increases in cellular levels of p-survivin at the time just before when the cells were subjected to OGD. We also documented that this increase in p-survivin levels was significantly attenuated if PI3-kinase was inhibited during HP. These changes were confirmed by confocal microscopy. Under control conditions, p-survivin was expressed at low levels in the nucleus...
but the intensity of p-survivin expression was notably enhanced in response to HP (Fig. 6B, middle). The resultant attenuation of HP-induced increases in p-survivin protein levels by LY-294002 was evidenced by lower p-survivin staining intensities, similar to those observed under control conditions (Fig. 6B, bottom). Together, these results implicate that a p-Akt-dependent phosphorylation of survivin contributes to the antiapoptotic effect of HP on HBMECs.

DISCUSSION

Results of the present study indicate that HP increases the resistance of cerebral endothelial cells to ischemia-reperfusion-induced apoptotic cell death. HP-mediated protection was characterized by the attenuation of nuclear AIF translocation and nuclear PARP-1 cleavage. Our studies showed that this reduction in apoptosis resulted, in part, from the phosphorylation-based activation of the IAP protein survivin, secondary to an HP-induced activation of PI3-kinase and the formation of p-Akt.

The cerebral vascular endothelium is an extremely active tissue responsible for regulating the trafficking of cells, substrates, and other molecules across the blood-brain barrier; for controlling vasomotor tone and reactivity; and for maintaining homeostasis at the blood-vascular wall interface (2). Postischemic microvascular dysfunction involving each of these aforementioned regulatory properties is now a well-established sequela in the stroke-affected cortex (17), and, as such, protection of the “neurovascular unit” is considered an essential component of stroke therapy (27). For obvious reasons, cell culture models of cerebrovascular endothelium are useful for elucidating mechanisms of ischemic injury and protection that are considerably more difficult to identify in vivo. To date, although cultured cerebral endothelial cells from rat (23) and bovine (40) brain have been employed to study mechanisms of cellular tolerance to TNF-α (23) and heat stress (40), only one model on ischemic tolerance has been published (4) using mouse cerebral endothelial cells. The present study is the first to demonstrate preconditioning-induced protection against OGD-induced apoptotic injury in human cerebral endothelial cells, underscoring the potential clinical applications of cerebrovascular preconditioning. We also show for the first time that a noninjurious preconditioning regimen involving hypoxia, not brief ischemia, can serve as an effective preconditioning stimulus. As alluded to above, the protection afforded by our HP stimulus against OGD-induced HBMEC death was antiapoptotic in nature, as evidenced in our model as reductions in the
caspase-independent nuclear translocation of AIF and the caspase-dependent cleavage of nuclear PARP-1, both of which correlate with transferase-mediated dUTP nick-end labeling positivity and other markers of apoptosis (61). The ability of HP to abrogate apoptotic cell death in cerebrovascular endothelium is in line with observations that preconditioning can prevent AIF translocation and/or PARP-1 cleavage in other cells (30, 46). Taken together with the recent finding in mouse cerebrovascular endothelial cell culture that preconditioning reduces the OGD-induced release of intracellular LDH (4), a prototypical marker of necrotic cell death (32), one would conclude that preconditioning acts on multiple cell death pathways in cerebral endothelium to reduce ischemia-induced death and dysfunction.

Our finding that HP promoted a PI3-kinase-dependent increase in the phosphorylation of Akt in HBMECs is consistent with similar observations of hypoxia-induced Akt phosphorylation in other cell types (3, 6, 56, 60). The detailed mechanisms by which PI3-kinase is activated by hypoxia require further elucidation (11, 60). Whether p-Akt is causal to HP-induced cytoprotection appears to be stimulus, cell type, and model dependent. In cultured neurons, Akt does not appear to be essential to OGD preconditioning-induced protection against more severe OGD-mediated injury (24, 26). However, when hypoxia is used as the preconditioning stimulus, protection of cultured neurons from ischemia and other death-inducing stimuli is p-Akt dependent (56). Moreover, the resistance of neuronal PC12 cells to serum withdrawal-induced apoptosis afforded by concomitant hypoxia is also dependent on Akt (3), as was HP-induced protection of cultured hepatocytes (9) and cardiomyocytes (51). Demonstrating a role for Akt in cerebral ischemic tolerance in vivo has been controversial (39, 58) and...
may reflect the use of brief global hypoxia-ischemia as a preconditioning stimulus in these models and/or the differential extent to which neurons, glia, and endothelial cells contributed to elevations in tissue homogenate levels of p-Akt and the inability to identify which cells account for the effects of intracerebroventricularly administrated PI3-kinase inhibitors (39, 58). Our present results indicate that cerebral endothelial cell preconditioning by hypoxia requires p-Akt. Other endothelial cell models of HP also show a dependence on Akt for the induced tolerance exhibited by these cells to a variety of injurious insults (1, 62). Collectively, the data suggest that Akt may be critical to HP-induced protection in this particular vascular cell (48), independent of the tissue of origin, and that, with cerebral ischemic tolerance, non-Akt-dependent survival pathways may be operative in neurons and glia.

The mechanisms by which Akt exerts cytoprotective, prosurvival effects require further clarification. Considerable evidence indicates that p-Akt exerts antiapoptotic effects through the phosphorylation and deactivation of multiple targets, including Bad, caspase 9, glycogen synthase kinase-3, and the FOXO family of forkhead transcription factors. Activation of the PI3-kinase/Akt pathway inhibits the opening of the mitochondrial permeability transition pore (29), thereby preventing AIF release and translocation. Our demonstration by PI3-kinase inhibition that OGD-triggered AIF translocation from the mitochondria to the nucleus was negatively regulated by HP-induced protection in this particular vascular cell (48), independent of the tissue of origin, and that, with cerebral ischemic tolerance, non-Akt-dependent survival pathways may be operative in neurons and glia.

Although survivin is well established as a survival factor in the embryogenesis and oncology literature, our study is the first to document a role for p-survivin in establishing the antiapoptotic phenotype characteristic of ischemic tolerance in endothelial cells or other resident brain cells. Normally, survivin expression in resting endothelial cells is low (28) but can be upregulated in a cell cycle-dependent manner by VEGF (42, 50) and angiopoietin-1 (44) as part of an angiogenic phenotype. In addition, survivin upregulation may be an endogenous response on the part of endothelial cells to combat injury-inducing stimuli like ischemia (14) and other lesions (7). The present results indicate that mild hypoxia may also serve to upregulate survivin expression, consistent with findings in cultured endothelial cells from coronary artery (62) and in cancer cell lines (57). In vivo, hypoxia caused a doubling of survivin mRNA levels in brain homogenates (14), and we observed increases in p-survivin protein levels in whole cell lysates of adult mouse brain for 24 h after systemic hypoxia.
(unpublished observations), but the extent to which cerebral endothelial cells contributed to the measured change in whole brain remains unclear. Given that the hypoxia-responsive transcription factor called hypoxia-inducible factor-1α (HIF-1α) binds to the survivin promoter (45) and can activate survivin transcription under hypoxic conditions (10), HIF-1α may drive survivin gene transcription in response to HP. Taken together, we contend that upregulation of endothelial survivin by HP contributes to the increased resistance of these cells to apoptotic death following ischemia-reperfusion.

As with the other IAP family members, the molecular basis of the ability of survivin to block apoptotic cell death is still under investigation. Evidence to date indicates that survivin suppresses both caspase-dependent and -independent apoptosis after injurious insults (35, 55). In our study, the HP-mediated attenuation of both AIF translocation and PARP-1 cleavage following OGD may be secondary to a p-Akt-dependent increase in survivin activity. By stabilizing the mitochondrial membrane, survivin attenuates the release of both cytochrome c and AIF (7). Moreover, the baculoviral IAP repeats domain of p-survivin binds to particular caspases and prevents their activation (34, 42). In endothelial cells, VEGF-induced survivin expression specifically inhibits caspase-3 activation by different apoptosis-inducing stimuli (37). In turn, the attenuation of caspase activation by survivin likely accounts for the reduced cleavage of PARP-1, a caspase substrate, that we measured in preconditioned endothelium. Overall, the abrogation of the extent of endothelial ischemic tolerance by PI3-kinase inhibition in our study, in conjunction with a documented reduction in p-survivin levels, is strongly supportive of the hypothesis that p-Akt-driven increases in endothelial p-survivin expression contributes importantly to preconditioning cytoprotection in cerebral endothelium. Survivin may also promote cell viability by binding to the molecular chaperone heat shock protein 90 (19) and other cell cycle-dependent mechanisms (41) that are not strictly antiapoptotic.

There are many ways in which viable, ischemia-tolerant endothelial cells could contribute to reductions in lesion severity following cerebral ischemia. Lower levels of posts ischemic inflammation, as a result of decreases in the expression of proinflammatory adhesion molecules (4, 59) and neutrophil-endothelial adherence (5), and improved endothelium-dependent vasoactive response are phenotypic changes documented in vitro that would be beneficial to the ischemic brain (4, 5, 16, 33, 59). Better preservation of homeostasis at the endothelial-blood interface may also result from the anti-inflammatory effects of endothelially derived nitric oxide, secondary to a preconditioning-induced, Akt-dependent phosphorylation of endothelial nitric oxide synthase (25); the HP-induced increase in p-Akt levels measured in our model is consistent with this possibility. Improved tissue perfusion, intact vascular reactivity, and maintained blood-brain barrier integrity may be other in vivo manifestations of cerebral endothelial cell tolerance (22). Finally, longer-term posts ischemic angiogenesis and microvascular remodeling will also be optimized by the enhanced endothelial cell viability achieved by prior preconditioning.

In summary, the present study introduced and utilized a new in vitro model of HP-induced ischemic tolerance of cerebral endothelium to demonstrate that activation of PI3-kinase, the phosphorylation of Akt, and a resultant increase in survivin phosphorylation collectively contribute to the protection from OGD-induced apoptosis afforded by HP. That this protection was documented in human endothelium underscores the potential for translational application of endothelial preconditioning regimens to patients with stroke. Further studies are needed to elucidate other downstream targets of p-Akt that may mediate cerebral endothelial protection from ischemic injury as well as to define the mechanistic basis of the antiapoptotic effect of survivin in ischemic endothelium.

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REFERENCES


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