Frontiers in Neuroscience 2017 vol.11 NJUL

Molecular bases of brain preconditioning

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Abstract

© 2017 Deryagin, Gavrilova, Gainutdinov, Golubeva, Andrianov, Yafarova, Buravkov and Koshelev. Preconditioning of the brain induces tolerance to the damaging effects of ischemia and prevents cell death in ischemic penumbra. The development of this phenomenon is mediated by mitochondrial adenosine triphosphate-sensitive potassium (KATP+) channels and nitric oxide signaling (NO). The aim of this study was to investigate the dynamics of molecular changes in mitochondria after ischemic preconditioning (IP) and the effect of pharmacological preconditioning (PhP) with the KATP+-channels opener diazoxide on NO levels after ischemic stroke in rats. Immunofluorescence-histochemistry and laser-confocal microscopy were applied to evaluate the cortical expression of electron transport chain enzymes, mitochondrial KATP+-channels, neuronal and inducible NO-synthases, as well as the dynamics of nitrosylation and nitration of proteins in rats during the early and delayed phases of IP. NO cerebral content was studied with electron paramagnetic resonance (EPR) spectroscopy using spin trapping. We found that 24 h after IP in rats, there is a two-fold decrease in expression of mitochondrial KATP+-channels ($p = 0.012$) in nervous tissue, a comparable increase in expression of cytochrome c oxidase ($p = 0.008$), and a decrease in intensity of protein S-nitrosylation and nitration ($p = 0.0004$ and $p = 0.001$, respectively). PhP led to a 56% reduction of free NO concentration 72 h after ischemic stroke simulation ($p = 0.002$). We attribute this result to the restructuring of tissue energy metabolism, namely the provision of increased catalytic sites to mitochondria and the increased elimination of NO, which prevents a decrease in cell sensitivity to oxygen during subsequent periods of severe ischemia.

http://dx.doi.org/10.3389/fnins.2017.00427

Keywords

ATP-sensitive potassium channels, Ischemic preconditioning, Mitochondria, Neuroprotection, Nitric oxide

References

[1] Andrukhiv, A., Costa, A. D., West, I. C., and Garlid, K. D. (2006). Opening mitoKATP increases superoxide generation from complex I of the electron transport chain. Am. J. Physiol. Heart Circ. Physiol. 291, 2067-2074. doi: 10.1152/ajpheart.00272.2006

[2] Antunes, F., Boveris, A., and Cadenas, E. (2007). On the biologic role of the reaction of NO with oxidized cytochrome coxidase. Antioxid. Redox Signal. 9, 1569-1579. doi: 10.1089/ars.2007.1677

[3] Aune, S. E., Herr, D. J., Kutz, C. J., and Menick, D. R. (2015). Histone deacetylases exert class-specific roles in conditioning the brain and heart against acute ischemic injury. Front. Neurol. 6:e145. doi: 10.3389/fneur.2015.00145

[4] Bajgar, R., Seetharaman, S., Kowaltowski, A. J., Garlid, K. D., and Paucek, P. (2001). Identification and properties of a novel intracellular (mitochondrial) ATP-sensitive potassium channel in brain. J. Biol. Chem. 276, 33369-33374. doi: 10.1074/jbc.M103320200

[5] Barone, F. C., White, R. F., Spera, P. A., Ellison, J., Currie, R. W., Wang, X., et al. (1998). Ischemic preconditioning and brain tolerance: temporal histological and functional outcomes, protein synthesis requirement, and interleukin-1 receptor antagonist and early gene expression. Stroke 29, 1937-1951. doi: 10.1161/01.STR.29.9.1937

[6] Barr, D., Jiang, J., and Weber, R. T. (2000). How to Quantitate Nitroxide Spin Adducts Using TEMPOL. EPR Division, Bruker, SpinReport, 3-6.

[7] Bartz, R. R., Suliman, H. B., and Piantadosi, C. A. (2015). Redox mechanisms of cardiomyocyte mitochondrial protection. Front. Physiol. 6:e291. doi: 10.3389/fphys.2015.00291

[8] Basu, S., Azarova, N. A., Font, M. D., King, S. B., Hogg, N., Gladwin, M. T., et al. (2008). Nitrite reductase activity of cytochrome C. J. Biol. Chem. 283, 32590-32597. doi: 10.1074/jbc.M806934200

[9] Bolanos, J. P., and Almeida, A. (1999). Roles of nitric oxide in brain hypoxia-ischemia. Biochim. Biophys. Acta 1411, 415-436. doi: 10.1016/S0005-2728(99)00030-4

[10] Brown, G. C., and Cooper, C. E. (1994). Nanomolar concentrations of nitric oxide reversibly inhibit synaptosomal respiration by competing with oxygen at cytochrome oxidase. FEBS Lett. 356, 295-298. doi: 10.1016/0014-5793(94)01290-3

[11] Brudvig, G. W., Stevens, T. H., and Chan, S. I. (1980). Reactions of nitric oxide with cytochrome c oxidase. Biochemistry 19, 5275-5285. doi: 10.1021/bi00564a020

[12] Brunori, M., Giuffrè, A., Forte, E., Mastronicola, D., Barone, M. C., and Sarti, P. (2004). Control of cytochrome c oxidase activity by nitric oxide. Biochim. Biophys. Acta 1655, 365-371. doi: 10.1016/j.bbabio.2003.06.008

[13] Brustovetsky, T., Shalbuyeva, N., and Brustovetsky, N. (2005). Lack of manifestations of diazoxide/5-hydroxydecanoate-sensitive KATP channel in rat brain nonsynaptosomal mitochondria. J. Physiol. 568, 47-59. doi: 10.1113/jphysiol.2005.091199

[14] Cabrera, J. A., Ziemba, E. A., Colbert, R., Anderson, L. B., Sluiter, W., Duncker, D. J., et al. (2012). Altered expression of mitochondrial electron transport chain proteins and improved myocardial energetic state during late ischemic preconditioning. Am. J. Physiol. Heart Circ. Physiol. 302, H1974-H1982. doi: 10.1152/ajpheart.00372.2011

[15] Calabrese, E. J. (2016). Pre- and post-conditioning hormesis in elderly mice, rats, and humans: its loss and restoration. Biogerontology 17, 681-702. doi: 10.1007/s10522-016-9646-8

[16] Chen, S. H., Fung, P. C., and Cheung, R. T. (2002). Neuropeptide Y-Y1 receptor modulates nitric oxide level during stroke in the rat. Free Radic. Biol. Med. 32, 776-784. doi: 10.1016/S0891-5849(02)00774-8

[17] Chouchani, E. T., Methner, C., Nadtochiy, S. M., Logan, A., Pell, V. R., Ding, S., et al. (2013). Cardioprotection by S-nitrosation of a cysteine switch on mitochondrial complex I. Nat. Med. 19, 753-759. doi: 10.1038/nm.3212

[18] Correia, S. C., Carvalho, C., Cardoso, S., Santos, R. X., Santos, M. S., Oliveira, C. R., et al. (2010). Mitochondrial preconditioning: a potential neuroprotective strategy. Front. Aging Neurosci. 2:e138. doi: 10.3389/fnagi.2010.00138

[19] Cuomo, O., Vinciguerra, A., Cerullo, P., Anzilotti, S., Brancaccio, P., Bilo, L., et al. (2015). Ionic homeostasis in brain conditioning. Front. Neurosci. 9:e277. doi: 10.3389/fnins.2015.00277

[20] Dedkova, E. N., and Blatter, L. A. (2009). Characteristics and function of cardiac mitochondrial nitric oxide synthase. J. Physiol. 587, 851-872. doi: 10.1113/jphysiol.2008.165423

[21] de Lima Portella, R., Lynn Bickta, J., and Shiva, S. (2015). Nitrite confers preconditioning and cytoprotection after ischemia/reperfusion injury through the modulation of mitochondrial function. Antioxid. Redox Signal. 23, 307-327. doi: 10.1089/ars.2015.6260

[22] Deryagin, O. G., Gavrilova, S. A., Buravkov, S. V., Andrianov, V. V., Yafarova, G. G., Gainutdinov, Kh. L., et al. (2016). The role of ATP-dependent potassium channels and nitric oxide system in the neuroprotective effect of preconditioning. Zh. Nevrol. Psikhiatr. Im. S. S. Korsakova 8, 16-22. doi: 10.17116/jnevro20161168217-23

[23] Ding, Z. M., Wu, B., Zhang, W. Q., Lu, X. J., Lin, Y. C., Geng, Y. J., et al. (2012). Neuroprotective effects of ischemic preconditioning and postconditioning on global brain ischemia in rats through the same effect on inhibition of apoptosis. Int. J. Mol. Sci. 13, 6089-6101. doi: 10.3390/ijms13056089

[24] Dröse, S. (2013). Differential effects of complex II on mitochondrial ROS production and their relation to cardioprotective pre- and postconditioning. Biochim. Biophys. Acta 1827, 578-587. doi: 10.1016/j.bbabio.2013.01.004

[25] Elfering, S. L., Sarkela, T. M., and Giulivi, C. (2002). Biochemistry of mitochondrial nitric-oxide synthase. J. Biol. Chem. 277, 38079-38086. doi: 10.1074/jbc.M205256200

[26] Ezzati, M., Bainbridge, A., Broad, K. D., Kawano, G., Oliver-Taylor, A., Rocha-Ferreira, E., et al. (2016). Immediate remote ischemic postconditioning after hypoxia ischemia in piglets protects cerebral white matter but not grey matter. J. Cereb. Blood Flow Metab. 36, 1396-1411. doi: 10.1177/0271678X15608862

[27] Foster, D. B., Ho, A. S., Rucker, J., Garlid, A. O., Chen, L., Sidor, A., et al. (2012). Mitochondrial ROMK channel is a molecular component of mitoK(ATP). Circ. Res. 111, 446-454. doi: 10.1161/CIRCRESAHA.112.266445

[28] Foster, D. B., Rucker, J. J., and Marbán, E. (2008). Is Kir6.1 a subunit of mitoK(ATP)? Biochem. Biophys. Res. Commun. 366, 649-656. doi: 10.1016/j.bbrc.2007.11.154

[29] Foster, M. N., and Coetzee, W. A. (2016). KATP channels in the cardiovascular system. Physiol. Rev. 96, 177-252. doi: 10.1152/physrev.00003.2015

[30] Gainutdinov, Kh. L., Andrianov, V. V., Iyudin, V. S., Yurtaeva, S. V., Jafarova, G. G., Faisullina, R. I., et al. (2013). EPR study of nitric oxide production in rat tissues under hypokinesia. Biophysics 58, 203-205. doi: 10.1134/S0006350913020073

[31] Gainutdinov, Kh. L., Gavrilova, S. A., Iyudin, V. S., Golubeva, A. V., Davydova, M. P., Jafarova, G. G., et al. (2011). EPR study of the intensity of the nitric oxide production in rat brain after ischemic stroke. Appl. Magn. Reson. 40, 267-278. doi: 10.1007/s00723-011-0207-7

[32] Gao, Z., Sierra, A., Zhu, Z., Koganti, S. R., Subbotina, E., and Maheshwari, A. (2016). Loss of ATP-sensitive potassium channel surface expression in heart failure underlies dysregulation of action potential duration and myocardial vulnerability to injury. PLoS ONE 11:e0151337. doi: 10.1371/journal.pone.0151337

[33] Garlid, A. O., Jaburek, M., Jacobs, J. P., and Garlid, K. D. (2013). Mitochondrial reactive oxygen species: which ROS signals cardioprotection? Am. J. Physiol. Heart Circ. Physiol. 305, 960-968. doi: 10.1152/ajpheart.00858.2012

[34] Gibson, Q. H., and Greenwood, C. (1963). Reactions of cytochrome oxidase with oxygen and carbon monoxide. Biochem. J. 86, 541-554. doi: 10.1042/bj0860541

[35] Giuffrè, A., Barone, M. C., Mastronicola, D., D'Itri, E., Sarti, P., and Brunori, M. (2000). Reaction of nitric oxide with the turnover intermediates of cytochrome c oxidase: reaction pathway and functional effects. Biochemistry 39, 15446-15453. doi: 10.1021/bi000447k

[36] Golwala, N. H., Hodenette, C., Murthy, S. N., Nossaman, B. D., and Kadowitz, P. J. (2009). Vascular responses to nitrite are mediated by xanthine oxidoreductase and mitochondrial aldehyde dehydrogenase in the rat. Can. J. Physiol. Pharmacol. 87, 1095-1101. doi: 10.1139/Y09-101

[37] Guo, D., Nguyen, T., Ogbi, M., Tawfik, H., Ma, G., Yu, Q., et al. (2007). Protein kinase C-epsilon coimmunoprecipitates with cytochrome oxidase subunit IV and is associated with improved cytochrome-c oxidase activity and cardioprotection. Am. J. Physiol. Heart Circ. Physiol. 293, H2219-H2230. doi: 10.1152/ajpheart.01306.2006

[38] Halestrap, A. P. (1987). The regulation of oxidation of fatty acids and other substrates in rat heart mitochondria by changes in the matrix volume induced by osmotic strength, valinomycin and Ca2+. Biochem. J. 244, 159-164. doi: 10.1042/bj2440159

[39] Hassouna, A., Loubani, M., Matata, B. M., Fowler, A., Standen, N. B., and Galiñanes, M. (2006). Mitochondrial dysfunction as the cause of the failure to precondition the diabetic human myocardium. Cardiovasc. Res. 69, 450-458. doi: 10.1016/j.cardiores.2005.11.004

[40] Holmuhamedov, E. L., Jahangir, A., Oberlin, A., Komarov, A., Colombini, M., and Terzic, A. (2004). Potassium channel openers are uncoupling protonophores: implication in cardioprotection. FEBS Lett. 568, 167-170. doi: 10.1016/j.febslet.2004.05.031

[41] Houten, S. M., and Wanders, R. J. (2010). A general introduction to the biochemistry of mitochondrial fatty acid ß-oxidation. J. Inherit. Metab. Dis. 33, 469-477. doi: 10.1007/s10545-010-9061-2

[42] Illi, B., Colussi, C., Grasselli, A., Farsetti, A., Capogrossi, M. C., and Gaetano, C. (2009). NO sparks off chromatin: tales of a multifaceted epigenetic regulator. Pharmacol. Ther. 123, 344-352. doi: 10.1016/j.pharmthera.2009.05.003

[43] Ishida, H., Higashijima, N., Hirota, Y., Genka, C., Nakazawa, H., Nakaya, H., et al. (2004). Nicorandil attenuates the mitochondrial Ca2+ overload with accompanying depolarization of the mitochondrial membrane in the heart. Naunyn Schmiedebergs. Arch. Pharmacol. 369, 192-197. doi: 10.1007/s00210-003-0851-z

[44] Jaburek, M., Costa, A. D., Burton, J. R., Costa, C. L., and Garlid, K. D. (2006). Mitochondrial PKC epsilon and mitochondrial ATP-sensitive K+ channel copurify and coreconstitute to form a functioning signaling module in proteoliposomes. Circ. Res. 99, 878-883. doi: 10.1161/01.RES.0000245106.80628.d3

[45] Jiang, M. T., Nakae, Y., Ljubkovic, M., Kwok, W. M., Stowe, D. F., and Bosnjak, Z. J. (2007). Isoflurane activates human cardiac mitochondrial adenosine triphosphate-sensitive K+ channels reconstituted in lipid bilayers. Anesth. Analg. 105, 926-932. doi: 10.1213/01.ane.0000278640.81206.92

[46] Jung, K. H., Chu, K., Ko, S. Y., Lee, S. T., Sinn, D. I., Park, D. K., et al. (2006). Early intravenous infusion of sodium nitrite protects brain against in vivo ischemia-reperfusion injury. Stroke 37, 2744-2750. doi: 10.1161/01.STR.0000245116.40163.1c

[47] Kalogeris, T., Bao, Y., and Korthuis, R. J. (2014). Mitochondrial reactive oxygen species: a double edged sword in ischemia/reperfusion vs preconditioning. Redox Biol. 2, 702-714. doi: 10.1016/j.redox.2014.05.006

[48] Katakam, P. V., Dutta, S., Sure, V. N., Grovenburg, S. M., Gordon, A. O., Peterson, N. R., et al. (2016). Depolarization of mitochondria in neurons promotes activation of nitric oxide synthase and generation of nitric oxide. Am. J. Physiol. Heart Circ. Physiol. 310, H1097-H1106. doi: 10.1152/ajpheart.00759.2015

[49] Katakam, P. V., Jordan, J. E., Snipes, J. A., Tulbert, C. D., Miller, A. W., and Busija, D. W. (2007). Myocardial preconditioning against ischemia-reperfusion injury is abolished in Zucker obese rats with insulin resistance. Am. J. Physiol. Regul. Integr. Comp. Physiol. 292, R920-R926. doi: 10.1152/ajpregu.00520.2006

[50] Katakam, P. V., Wappler, E. A., Katz, P. S., Rutkai, I., Institoris, A., Domoki, F., et al. (2013). Depolarization of mitochondria in endothelial cells promotes cerebral artery vasodilation by activation of nitric oxide synthase. Arterioscler. Thromb. Vasc. Biol. 33, 752-759. doi: 10.1161/ATVBAHA.112.300560

[51] Kim, M. Y., Kim, M. J., Yoon, I. S., Ahn, J. H., Lee, S. H., Baik, E. J., et al. (2006). Diazoxide acts more as a PKC-epsilon activator, and indirectly activates the mitochondrial K(ATP) channel conferring cardioprotection against hypoxic injury. Br. J. Pharmacol. 149, 1059-1070. doi: 10.1038/sj.bjp.0706922

[52] Kirino, T. (2002). Ischemic tolerance. J. Cereb. Blood Flow Metab. 22, 1283-1296. doi: 10.1097/01.WCB.0000040942.89393.88

[53] Kitamura, Y., Matsuoka, Y., Nomura, Y., and Taniguchi, T. (1998). Induction of inducible nitric oxide synthase and heme oxygenase-1 in rat glial cells. Life Sci. 62, 1717-1721. doi: 10.1016/S0024-3205(98)00134-9

[54] Konstas, A. A., Dabrowski, M., Korbmacher, C., and Tucker, S. J. (2002). Intrinsic sensitivity of Kir1.1 (ROMK) to glibenclamide in the absence of SUR2B. implications for the identity of the renal ATP-regulated secretory K+ channel. J. Biol. Chem. 277, 21346-21351. doi: 10.1074/jbc.M202005200

[55] Korichneva, I., Hoyos, B., Chua, R., Levi, E., and Hammerling, U. (2002). Zinc release from protein kinase C as the common event during activation by lipid second messenger or reactive oxygen. J. Biol. Chem. 277, 44327-44331. doi: 10.1074/jbc.M205634200

[56] Lacza, Z., Snipes, J. A., Kis, B., Szabó, C., Grover, G., and Busija, D. W. (2003a). Investigation of the subunit composition and the pharmacology of the mitochondrial ATP-dependent K+ channel in the brain. Brain Res. 994, 27-36. doi: 10.1016/j.brainres.2003.09.046

[57] Lacza, Z., Snipes, J. A., Miller, A. W., Szabó, C., Grover, G., and Busija, D. W. (2003b). Heart mitochondria contain functional ATP-dependent K+ channels. J. Mol. Cell. Cardiol. 35, 1339-1347. doi: 10.1016/S0022-2828(03)00249-9

[58] Li, H., Hemann, C., Abdelghany, T. M., El-Mahdy, M. A., and Zweier, J. L. (2012). Characterization of the mechanism and magnitude of cytoglobin-mediated nitrite reduction and nitric oxide generation under anaerobic conditions. J. Biol. Chem. 287, 36623-36633. doi: 10.1074/jbc.M112.342378

[59] Li, H., Samouilov, A., Liu, X., and Zweier, J. L. (2001). Characterization of the magnitude and kinetics of xanthine oxidase-catalyzed nitrite reduction. Evaluation of its role in nitric oxide generation in anoxic tissues. J. Biol. Chem. 276, 24482-24489. doi: 10.1074/jbc.M011648200

[60] Lim, K. H., Javadov, S. A., Das, M., Clarke, S. J., Suleiman, M. S., and Halestrap, A. P. (2002). The effects of ischaemic preconditioning, diazoxide and 5-hydroxydecanoate on rat heart mitochondrial volume and respiration. J. Physiol. 545, 961-974. doi: 10.1113/jphysiol.2002.031484

[61] Lim, S. Y., and Hausenloy, D. J. (2012). Remote ischemic conditioning: from bench to bedside. Front. Physiol. 3:e27. doi: 10.3389/fphys.2012.00027

[62] Liu, D., Lu, C., Wan, R., Auyeung, W. W., and Mattson, M. P. (2002). Activation of mitochondrial ATP-dependent potassium channels protects neurons against ischemia-induced death by a mechanism involving suppression of Bax translocation and cytochrome c release. J. Cereb. Blood Flow Metab. 22, 431-443. doi: 10.1097/00004647-200204000-00007

[63] Madungwe, N. B., Zilberstein, N. F., Feng, Y., and Bopassa, J. C. (2016). Critical role of mitochondrial ROS is dependent on their site of production on the electron transport chain in ischemic heart. Am. J. Cardiovasc. Dis. 6, 93-108.

[64] Manukhina, E. B., Malyshev, I. Y., Smirin, B. V., Mashina, S. Y., Saltykova, V. A., and Vanin, A. F. (1999). Production and storage of nitric oxide in adaptation to hypoxia. Nitric Oxide 3, 393-401. doi: 10.1006/niox.1999.0244

[65] Marshall, J. M., Thomas, T., and Turner, L. (1993). A link between adenosine, ATP-sensitive K+ channels, potassium and muscle vasodilatation in the rat in systemic hypoxia. J. Physiol. 472, 1-9. doi: 10.1113/jphysiol.1993.sp019931

[66] Maslov, L. N., Khaliulin, I. G., and Podoksenov, Yu. K. (2012). Neuroprotective and cardioprotective effects of hypothermic preconditioning. Patol. Fiziol. Eksp. Ter. 1, 67-72

[67] McLeod, C. J., Jeyabalan, A. P., Minners, J. O., Clevenger, R., Hoyt, R. F. Jr., and Sack, M. N. (2004). Delayed ischemic preconditioning activates nuclear-encoded electron-transfer-chain gene expression in parallel with enhanced postanoxic mitochondrial respiratory recovery. Circulation 110, 534-539. doi: 10.1161/01.CIR.0000136997.53612.6C

[68] Mikoyan, V. D., Kubrina, L. N., Serezhenkov, V. A., Stukan, R. A., and Vanin, A. F. (1997). Complexes of Fe2+ with diethyldithiocarbamate or N-methyl-D-glucamine dithiocarbamate as traps of nitric oxide in animal tissues. Biochim. Biophys. Acta 1336, 225-2340. doi: 10.1016/S0304-4165(97)00032-9

[69] Mironova, G. D., Kachaeeva, E. V., Krylova, I. B., Rodionova, O. M., Balina, M. I., Evdokimova, N. R., et al. (2007). Mitochondrial ATP-dependent potassium channel. 2. The role of the channel in protection of the heart against ischemia. Vestn. Ross. Akad. Med. Nauk. 2, 44-49.

[70] Mironova, G. D., Negoda, A. E., Marinov, B. S., Paucek, P., Costa, A. D., Grigoriev, S. M., et al. (2004). Functional distinctions between the mitochondrial ATP-dependent K+ channel (mitoKATP) and its inward rectifier subunit (mitoKIR). J. Biol. Chem. 279, 32562-32568. doi: 10.1074/jbc.M401115200

[71] Mohiuddin, I., Chai, H., Lin, P. H., Lumsden, A. B., Yao, Q., and Chen, C. (2006). Nitrotyrosine and chlorotyrosine: clinical significance and biological functions in the vascular system. J. Surg. Res. 133, 143-149. doi: 10.1016/j.jss.2005.10.008

[72] Murata, M., Akao, M., O'Rourke, B., and Marbán, E. (2001). Mitochondrial ATP-sensitive potassium channels attenuate matrix Ca2+ overload during simulated ischemia and reperfusion: possible mechanism of cardioprotection. Circ. Res. 89, 891-898. doi: 10.1161/hh2201.100205

[73] Nandagopal, K., Dawson, T. M., and Dawson, V. L. (2001). Critical role for nitric oxide signaling in cardiac and neuronal ischemic preconditioning and tolerance. J. Pharmacol. Exp. Ther. 297, 474-478.

[74] Ortega, F. J., Gimeno-Bayon, J., Espinosa-Parrilla, J. F., Carrasco, J. L., Batlle, M., Pugliese, M., et al. (2012). ATP-dependent potassium channel blockade strengthens microglial neuroprotection after hypoxia-ischemia in rats. Exp. Neurol. 235, 282-296. doi: 10.1016/j.expneurol.2012.02.010

[75] Palacios-Callender, M., Hollis, V., Mitchison, M., Frakich, N., Unitt, D., and Moncada, S. (2007). Cytochrome c oxidase regulates endogenous nitric oxide availability in respiring cells: a possible explanation for hypoxic vasodilation. Proc. Natl. Acad. Sci. U.S.A. 104, 18508-18513. doi: 10.1073/pnas.0709440104

[76] Perez-Pinzon, M. A., Xu, G. P., Dietrich, W. D., Rosenthal, M., and Sick, T. J. (1997). Rapid preconditioning protects rats against ischemic neuronal damage after 3 but not 7 days of reperfusion following global cerebral ischemia. J. Cereb. Blood Flow Metab. 17, 175-182. doi: 10.1097/00004647-199702000-00007

[77] Perlman, D. H., Bauer, S. M., Ashrafian, H., Bryan, N. S., Garcia-Saura, M. F., Lim, C. C., et al. (2009). Mechanistic insights into nitrite-induced cardioprotection using an integrated metabolomic/proteomic approach. Circ. Res. 104, 796-804. doi: 10.1161/CIRCRESAHA.108.187005

[78] Rana, A., Goyal, N., Ahlawat, A., Jamwal, S., Reddy, B. V., and Sharma, S. (2015). Mechanisms involved in attenuated cardio-protective role of ischemic preconditioning in metabolic disorders. Perfusion 30, 94-105. doi: 10.1177/0267659114536760

[79] Rybnikova, E., and Samoilov, M. (2015). Current insights into the molecular mechanisms of hypoxic pre- and postconditioning using hypobaric hypoxia. Front. Neurosci. 9:e388. doi: 10.3389/fnins.2015.00388

[80] Saikumar, P., and Kurup, C. K. (1985). Effect of administration of 2-methyl-4-dimethylaminoazobenzene on the half-lives of rat liver mitochondria and cytochrome oxidase. Biochim. Biophys. Acta 840, 127-133. doi: 10.1016/0304-4165(85)90169-2

[81] Samoilenkova, N. S., Gavrilova, S. A., Dubina, A. I., Khudoerkov, R. M., Pirogov, Ju. A., et al. (2007). Role of ATP-sensitive potassium channel in hypoxic and ischemic types of preconditioning in rat brain with focal ischemia. Regionarnoe Krovoobrashchenie i Mikrotsirkulyatsiya 6, 68-77.

[82] Samoilenkova, N. S., Gavrilova, S. A., and Koshelev, V. B. (2008). Neuroprotective and angioprotective effect of ischemic/hypoxic preconditioning of the brain. Regionarnoe Krovoobrashchenie i Mikrotsirkulyatsiya 1, 82-92.

[83] Sarti, P., Forte, E., Mastronicola, D., Giuffrè, A., and Arese, M. (2012). Cytochrome coxidase and nitric oxide in action: molecular mechanisms and pathophysiological implications. Biochim. Biophys. Acta 1817, 610-619. doi: 10.1016/j.bbabio.2011.09.002

[84] Sarti, P., Giuffré, A., Forte, E., Mastronicola, D., Barone, M. C., and Brunori, M. (2000). Nitric oxide and cytochrome c oxidase: mechanisms of inhibition and NO degradation. Biochem. Biophys. Res. Commun. 274, 183-187. doi: 10.1006/bbrc.2000.3117

[85] Sasaki, N., Sato, T., Ohler, A., O'Rourke, B., and Marbán, E. (2000). Activation of mitochondrial ATP-dependent potassium channels by nitric oxide. Circulation 101, 439-445. doi: 10.1161/01.CIR.101.4.439

[86] Schulz, R., and Ferdinandy, P. (2013). Does nitric oxide signaling differ in pre- and post-conditioning? Importance of S-nitrosylation vs. protein kinase G activation. Free Radic. Biol. Med. 54, 113-115. doi: 10.1016/j.freeradbiomed.2012.10.547

[87] Shen, B., and English, A. M. (2005). Mass spectrometric analysis of nitroxyl-mediated protein modification: comparison of products formed with free and protein-based cysteines. Biochemistry 44, 14030-14044. doi: 10.1021/bi0507478

[88] Shimizu, K., Lacza, Z., Rajapakse, N., Horiguchi, T., Snipes, J., and Busija, D. W. (2002). MitoK(ATP) opener, diazoxide, reduces neuronal damage after middle cerebral artery occlusion in the rat. Am. J. Physiol. Heart Circ. Physiol. 283, H1005-H1011. doi: 10.1152/ajpheart.00054.2002

[89] Shmonin, A. A., Baisa, A. E., Melnikova, E. V., Vavilov, V. N., and Vlasov, T. D. (2012). Protective effects of early ischemic preconditioning in focal cerebral ischemia in rats: the role of collateral blood circulation. Neurosci. Behav. Physiol. 42, 643-650. doi: 10.1007/s11055-012-9615-x

[90] Shukry, M., Kamal, T., Ali, R., Farrag, F., Almadaly, E., Saleh, A. A., et al. (2015). Pinacidil and levamisole prevent glutamate-induced death of hippocampal neuronal cells through reducing ROS production. Neurol. Res. 37, 916-923. doi: 10.1179/1743132815Y.0000000077

[91] Singh, H., Hudman, D., Lawrence, C. L., Rainbow, R. D., Lodwick, D., and Norman, R. I. (2003). Distribution of Kir6.0 and SUR2 ATP-sensitive potassium channel subunits in isolated ventricular myocytes. J. Mol. Cell. Cardiol. 35, 445-459. doi: 10.1016/S0022-2828(03)00041-5

[92] Sun, H. S., Xu, B., Chen, W., Xiao, A., Turlova, E., and Alibraham, A. (2015). Neuronal K(ATP) channels mediate hypoxic preconditioning and reduce subsequent neonatal hypoxic-ischemic brain injury. Exp. Neurol. 263, 161-171. doi: 10.1016/j.expneurol.2014.10.003

[93] Sun, J., Morgan, M., Shen, R. F., Steenbergen, C., and Murphy, E. (2007). Preconditioning results in S-nitrosylation of proteins involved in regulation of mitochondrial energetics and calcium transport. Circ. Res. 101, 1155-1163. doi: 10.1161/CIRCRESAHA.107.155879

[94] Swyers, T., Redford, D., and Larson, D. F. (2014). Volatile anesthetic-induced preconditioning. Perfusion 29, 10-15. doi: 10.1177/0267659113503975

[95] Talanov, E. Y., Pavlik, L. L., Mikheeva, I. B., Murzaeva, S. V., Ivanov, A. N., and Mironova, G. D. (2016). Ultrastructural localization of the ROMK potassium channel in rat liver and heart. Biochem. Moscow Suppl. Ser. A 10, 195-198. doi: 10.1134/S1990747816020100

[96] Tejero, J., Sparacino-Watkins, C. E., Ragireddy, V., Frizzell, S., and Gladwin, M. T. (2015). Exploring the mechanisms of the reductase activity of neuroglobin by site-directed mutagenesis of the heme distal pocket. Biochemistry 54, 722-733. doi: 10.1021/bi501196k

[97] Terpolilli, N. A., Moskowitz, M. A., and Plesnila, N. (2012). Nitric oxide: considerations for the treatment of ischemic stroke. J. Cereb. Blood Flow Metab. 32, 1332-1346. doi: 10.1038/jcbfm.2012.12

[98] Thuret, R., Saint Yves, T., Tillou, X., Chatauret, N., Thuillier, R., and Barrou, B. (2014). Ischemic pre- and post-conditioning: current clinical applications. Prog. Urol. 24, S56-S61. doi: 10.1016/s1166-7087(14)70065-x

[99] Tiso, M., Tejero, J., Basu, S., Azarov, I., Wang, X., Simplaceanu, V., et al. (2011). Human neuroglobin functions as a redox-regulated nitrite reductase. J. Biol. Chem. 286, 18277-18289. doi: 10.1074/jbc.M110.159541

[100] Tominaga, T., Sato, S., Ohnishi, T., and Ohnishi, S. T. (1994). Electron paramagnetic resonance (EPR) detection of nitric oxide produced during forebrain ischemia of the rat. J. Cereb. Blood Flow Metab. 14, 715-722. doi: 10.1038/jcbfm.1994.92

[101] Torres, J., Sharpe, M. A., Rosquist, A., Cooper, C. E., and Wilson, M. T. (2000). Cytochrome c oxidase rapidly metabolises nitric oxide to nitrite. FEBS Lett. 475, 263-266. doi: 10.1016/S0014-5793(00)01682-3

[102] Vadziuk, O. B., Chunikhin, O., and Kosterin, S. O. (2010). Effect of mitochondrial ATP-dependent potassium channel effectors diazoxide and glybenclamide on hydrodynamic diameter and membrane potential of the myometrial mitochondria. Ukr. Biokhim. Zh. 82, 40-47.

[103] Vanin, A. F., Huisman, A., and Van Faassen, E. E. (2003). Iron dithiocarbamate as spin trap for nitric oxide detection: pitfalls and successes. Methods Enzymol. 359, 27-42. doi: 10.1016/S0076-6879(02)59169-2

[104] Virgili, N., Mancera, P., Wappenhans, B., Sorrosal, G., Biber, K., Pugliese, M., et al. (2013). K(ATP) channel opener diazoxide prevents neurodegeneration: a new mechanism of action via antioxidative pathway activation. PLoS ONE 8:e75189. doi: 10.1371/annotation/0e045706-ea24-41db-be90-27d1cbcd35b1

[105] Wang, M., Qi, D. S., Zhou, C., Han, D., Li, P. P., Zhang, F., et al. (2016). Ischemic preconditioning protects the brain against injury via inhibiting CaMKII-nNOS signaling pathway. Brain Res. 1634, 140-149. doi: 10.1016/j.brainres.2016.01.008

[106] Wang, T., Qin, L., Liu, B., Liu, Y., Wilson, B., Eling, T. E., et al. (2004). Role of reactive oxygen species in LPS-induced production of prostaglandin E2 in microglia. J. Neurochem. 88, 939-947. doi: 10.1046/j.1471-4159.2003.02242.x

[107] Wang, W. W., Hu, S. Q., Li, C., Zhou, C., Qi, S. H., and Zhang, G. Y. (2010). Transduced PDZ1 domain of PSD-95 decreases Src phosphorylation and increases nNOS (Ser847) phosphorylation contributing to neuroprotection after cerebral ischemia. Brain Res. 1328, 162-170. doi: 10.1016/j.brainres.2010.02.055

[108] Wang, Y., Reis, C., Applegate, R. II., Stier, G., Martin, R., Zhang, J. H., et al. (2015). Ischemic conditioning-induced endogenous brain protection: applications pre-, per- or post-stroke. Exp. Neurol. 272, 26-40. doi: 10.1016/j.expneurol.2015.04.009

[109] Wojtovich, A. P., Smith, C. O., Haynes, C. M., Nehrke, K. W., and Brookes, P. S. (2013). Physiological consequences of complex II inhibition for aging, disease, and the mKATP channel. Biochim. Biophys. Acta 1827, 598-611. doi: 10.1016/j.bbabio.2012.12.007

[110] Xi, Q., Cheranov, S. Y., and Jaggar, J. H. (2005). Mitochondria-derived reactive oxygen species dilate cerebral arteries by activating Ca2+ sparks. Circ. Res. 97, 354-362. doi: 10.1161/01.RES.0000177669.29525.78

[111] Yamada, K., Ji, J. J., Yuan, H., Miki, T., Sato, S., Horimoto, N., et al. (2001). Protective role of ATP-sensitive potassium channels in hypoxia-induced generalized seizure. Science 292, 1543-1546. doi: 10.1126/science.1059829

[112] Yuan, Z., Liu, W., Liu, B., Schnell, A., and Liu, K. J. (2010). Normobaric hyperoxia delays and attenuates early nitric oxide production in focal cerebral ischemic rats. Brain Res. 1352, 248-254. doi: 10.1016/j.brainres.2010.07.010

[113] Zhou, M., He, H. J., Suzuki, R., Liu, K. X., Tanaka, O., Sekiguchi, M., et al. (2007). Localization of sulfonylurea receptor subunits, SUR2A and SUR2B, in rat heart. J. Histochem. Cytochem. 55, 795-804. doi: 10.1369/jhc.6A7104.2007