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A Death-Promoting Role for Extracellular Signal-Regulated Kinase

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ABSTRACT

Extracellular signal-regulated protein kinases 1 and 2 (ERK1/2), which are members of the mitogen-activated protein kinase superfamily, have been well characterized and are known to be involved in cell survival; however, recent evidence suggests that the activation of ERK1/2 also contributes to cell death in some cell types and organs under certain conditions. For example, ERK1/2 is activated in neuronal and renal epithelial cells upon exposure to oxidative stress and toxicants and deprivation of growth factors, and inhibition of the ERK pathway blocks apoptosis. ERK activation also occurs in animal models of ischemia- and trauma-induced brain injury and cisplatin-induced renal injury, and inactivation of ERK reduces the extent of tissue damage. In some studies, ERK has been implicated in apoptotic events upstream of mitochondrial cytochrome c release, whereas other studies have suggested the converse that ERK acts downstream of mitochondrial events and upstream of caspase-3 activation. ERK also can contribute to cell death through the suppression of the antiapoptotic signaling molecule Akt. Here we summarize the evidence and mechanism of ERK-induced apoptosis in both cell culture and in animal models.

General Cascades of Cell Death

Cell death is divided into at least two categories, apoptosis and necrotic cell death. Apoptosis is a tightly orchestrated series of events that requires ATP and includes potassium efflux, cell shrinkage, mitochondria protein release, and caspase activation (Yu et al., 2001; Boatright and Salvesen, 2003; Yu, 2003). In contrast, necrotic cell death is initiated by mitochondrial inhibition and the loss of ATP and is associated with the breakdown of the cytoskeleton, cellular swelling, and progressive increases in plasma membrane permeability (Majno and Joris, 1995; Chen et al., 2001; Harriman et al., 2002; Liu et al., 2004). In general, apoptosis usually involves individual noncontiguous cells, whereas necrotic cell death usually involves multiple contiguous cells (Columbano, 1995; Boatright and Salvesen, 2003). Interestingly, the extent of exposure to an insult determines the nature of cell death, and both forms can occur simultaneously in tissue; apoptosis results from milder insults, whereas necrosis follows more severe insults (Columbano, 1995; Majno and Joris, 1995).

Extensive studies to elucidate the mechanisms by which apoptosis is induced and transduced have resulted in the generally accepted theory that intrinsic and extrinsic mechanisms are involved (Fig. 1) (Fadeel and Orrenius, 2005; Kim et al., 2006). Intrinsic pathways are activated by specific stress stimuli and lead to mitochondrial cytochrome c release, the activation of caspase-9 through Apaf-1, and the activation of executioner caspases (e.g., caspase-3) (Fadeel and Orrenius, 2005). The extrinsic apoptotic pathway is initiated by the activation of death receptors, such as the TNF-α receptor and Fas, and caspase-8 (Kim et al., 2006). Activated caspase-8 can directly activate executioner caspases and/or induce cleavage of Bid to truncated Bid. Truncated Bid is translocated to the mitochondria, prompting cytochrome c release and subsequent activation of caspase-3 (Li et al., 1998; Runden et al., 1998).

Concomitant with the activation of apoptotic pathways, survival signaling pathways are activated. Among them, the...
phosphatidylinositol 3-kinase/Akt pathway is activated by many apoptotic stimuli and plays a critical role in balancing apoptosis (Yang et al., 2004). Although the ERK pathway is attributed to survival for many cell types, ERK activation is now thought to contribute to apoptosis as well.

**ERK Signaling Pathway**

ERK belongs to a family of mitogen-activated protein kinases (MAPKs) that comprises ERKs, c-Jun N-terminal kinase/stress-activated protein kinases, and p38 kinases. Within the ERK group, there are eight isoforms (i.e., ERK1, 2, 3, 4, 5, 6, 7, and 8) (Bogoyevitch and Court, 2004; Yoon and Seger, 2006) of which ERK1 and ERK2 have been extensively studied. ERK1 and ERK2 are regulated by the dual-specificity kinases MEK1 and MEK2 through phosphorylation at both a threonine and an adjacent tyrosine residue within a dual-specificity motif (Thr-Glu-Tyr). MEK1 and MEK2 can be activated by multiple MAPK kinase kinases, although Raf kinase family members typically serve as dedicated MEK1/2 activators (Garrington and Johnson, 1999). Low molecular weight G-proteins (Ras, Rac, Rho, Cdc42, etc.), each associated with growth factor receptor activation and cellular adhesion, can contribute to Raf activation either directly or indirectly (Peyssonaux and Eychene, 2001).

ERK1/2 also is activated in response to various stress stimuli through divergent mechanisms involving the Ras-Raf-MEK pathway (Strniskova et al., 2002; Kyoosseva, 2004; Roux and Blenis, 2004; Baines and Molkentin, 2005; Rennefahr et al., 2005). Depending upon the cell type, the stimulus, and the duration of activation, a variety of biological responses (i.e., cell proliferation, migration, differentiation, and apoptosis) are associated with ERK activation (Strniskova et al., 2002; Kyoosseva, 2004; Roux and Blenis, 2004; Baines and Molkentin, 2005; Rennefahr et al., 2005). This proapoptotic perspective of ERK will comprise the remainder of this review.

**ERK Signaling Mediates Apoptosis in Cultured Cells**

Bhat and Zhang (1999) first reported that inhibition of ERK using the MEK1 inhibitor PD98059 (2′-amino-3′-methoxyflavone) rescues oligodendrocytes from H2O2-induced cell death, and this observation was subsequently confirmed in HeLa cells (Wang et al., 2000), cortical neurons (Lesseis and Martin, 2002), and primary β-cells (Pavlovic et al., 2000) (Table 1). In renal cell lines (LLC-PK1 and OK) and primary cultures of renal proximal tubular cells, inhibition of ERK improved cell survival by inhibiting apoptosis after cisplatin exposure (Ishikawa and Kitamura, 2000; Nowak, 2002; Kim et al., 2005). The proapoptotic role of ERK in renal epithelial cells is not limited to cisplatin exposure; ERK activation is also associated with cell death induced by reactive oxygen species (ROS) (Tikoo et al., 2001; Ramachandiran et al., 2002; Dong et al., 2004), *Escherichia coli* toxins (Chen et al., 2004), zinc (Matsunaga et al., 2005), and cephaloridine (Kohda et al., 2003). ERK activation also has been implicated in cell death induced by deprivation of survival factors. For example, withdrawal of survival factors from mouse kidney proximal tubular epithelial cells led to a progressive increase in ERK1/2 activity, and inhibition of ERK1/2 maintained cell survival (Sinha et al., 2004). Finally, ERK1/2 activation is involved in doxorubicin-induced apoptosis in human hep-atomia cell lines (HepG2 and Huh-7) (Alexia et al., 2004), amylloid-induced neurotoxicity in primary hippocampal neurons (Medina et al., 2005), and CD40-mediated apoptosis in cholangiocytes (Ahmed-Choudhury et al., 2006).

Most of the above-mentioned studies addressed the role of ERK in apoptosis using MEK inhibitor PD98059 or U0126 (1,4-diamino-2,3-dicyano-1,4-bis(2-aminoethylthio)butadiene) (Alessi et al., 1995; Favata et al., 1998). Recently, Kim et al. (2005) used molecular approaches to examine the role of the ERK pathway in cell death of renal epithelial cells. They found that transient transfection of
constitutively active MEK1 increased H$_2$O$_2$-induced apoptosis, whereas the dominant-negative mutant of MEK1 led to an inhibition of H$_2$O$_2$-mediated cell death. Likewise, the dominant-negative mutant of MEK1 region (Sugino et al., 2000) and did not block cerebral end-ergicbils against ischemic cell death in the hippocampal CA1 region (Sugino et al., 2000) and did not block cerebral endo-

Finally, inhibition of ERK1/2 with PD98059 failed to protect medullary cells against ischemic cell death in these areas. In support of an anti-apoptotic role of ERK, Gonzalez-Zulueta et al. (2000) reported that activation of the Ras/ERK cascade was critical for medullary cell survival in these areas. In support of an anti-

ERK Signaling Mediates Injury-Induced Tissue Damage in Vivo

ERK-mediated cell death also has been reported in numerous animal models. In a mouse model of stroke induced by transient occlusion of the middle cerebral artery, an increase in phosphorylated ERK in the nuclei of cortical cells was detected and pretreatment with PD98059 blocked ERK phosphorylation, resulting in a 55% decrease in focal infarct volume at 22 h and a 36% decrease at 72 h (Alessandrini et al., 2002; Clausen et al., 2004). These results confirm the same model, researchers confirmed these results using two additional MEK1 inhibitors U0126 and SL327 (Namura et al., 2001, Wang et al., 2003, 2004b). In a gerbil model of forebrain ischemia induced by bilateral carotid artery occlusion, Namura et al. (2001) obtained similar results with MEK1 inhibitors. ERK also was rapidly activated in damaged tissue in a controlled cortical-impact model of traumatic injury in mice, and ERK pathway inhibition with PD98059 prior to trauma resulted in a significant reduction of cortical lesion volumes 7 days after trauma (Mori et al., 2002; Clausen et al., 2004). Confocal immunohistochemistry showed that phospho-ERK colocalized with the neuronal nuclei marker Neu-N in the injured brain (Fig. 1).

However, increased phospho-ERK1/2 staining was also detected in neurons that survived ischemic injury in a rat and mouse model of focal cerebral ischemia (Irving et al., 2000; Namura et al., 2001), suggesting that ERK1/2 activation may mediate cell survival in these areas. In support of an anti-apoptotic role of ERK, Gonzalez-Zulueta et al. (2000) reported that activation of the Ras/ERK cascade was critical for the development of ischemic tolerance in cortical neurons. Finally, inhibition of ERK1/2 with PD98059 failed to protect gerbils against ischemic cell death in the hippocampal CA1 region (Sugino et al., 2000) and did not block cerebral endo-

Mechanisms of ERK-Induced Apoptosis

ERK-Mediated Regulation of the Intrinsic Pathway

Because the intrinsic pathway is characterized by mitochondrial outer membrane permeabilization, cytochrome c release, and caspase activation, the association of ERK with these events has been investigated in vivo and in vitro. In vivo studies revealed that ERK1/2 acts upstream of caspase-3 in cisplatin-induced cell death in the kidney (Jo et al., 2005) and in the brain after ischemia/reperfusion (Wang et al., 2003). Using HeLa cells, Wang et al. (2000) showed that ERK1/2 inhibition blocks cytochrome c release and subsequent activation of caspase-3 in cisplatin-induced apoptosis. In a renal cell line (OK cells), Kim et al. (2005) reported that ERK activation is required for mitochondrial membrane depolarization, cytochrome c release, and caspase-3 activation after cisplatin exposure. Nowak (2002) reported that phosphorylated ERK1/2 was detected in mitochondria and associated with loss of mitochondrial function in cisplatin-treated primary cultures of renal proximal tubular cells. However, ERK inhibition blocked caspase-3 activation without affect-

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<th>Cell Types</th>
<th>Inducers</th>
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<tr>
<td>Oligodendrocyte</td>
<td>H$_2$O$_2$</td>
<td>Bhat and Zhang, 1999</td>
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<td>Hippocampal neurons</td>
<td>Amyloid</td>
<td>Medina et al., 2005</td>
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<td>Glial cells</td>
<td>Glutathione depletion</td>
<td>de Bernardo et al., 2004</td>
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<td>CGN (cerebellar granule neurons)</td>
<td>Low potassium</td>
<td>Subramaniam et al., 2003, 2004</td>
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<td>Pyramidal cells</td>
<td>Okadaic acid</td>
<td>Wong et al., 2003</td>
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<td>Renal proximal tubular cells</td>
<td>Cisplatin</td>
<td>Runden et al., 1998</td>
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<td>Hepatoma cell line (HeP2)</td>
<td>Doxorubicin</td>
<td>Nowak, 2002; Arany et al., 2004; Kim et al., 2005</td>
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<tr>
<td>HeLa (cervical carcinoma cells)</td>
<td>Cisplatin</td>
<td>Alexia et al., 2004</td>
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<td>Renal epithelial cells</td>
<td>Growth factors depletion</td>
<td>Wang et al., 2000</td>
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<td>Renal epithelial cells</td>
<td>Escherichia coli toxin</td>
<td>Sinha et al., 2004</td>
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<td>Renal epithelial cells</td>
<td>ROS</td>
<td>Chen et al., 2004</td>
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<tr>
<td>Osteoblastic cells</td>
<td>H$_2$O$_2$</td>
<td>Tikoo et al., 2001; Ramachandiran et al., 2002; Dong et al., 2004</td>
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<tr>
<td>Pancreatic β-cells</td>
<td>Interleukin-1β</td>
<td>Park et al., 2005</td>
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<td>TM4 cells (Sertoli cell line)</td>
<td>CD95L</td>
<td>Pavlovic et al., 2000</td>
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<tr>
<td>Lens epithelial cells</td>
<td>Calcium</td>
<td>Ulisse et al., 2000</td>
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<td>Bone marrow stromal cells</td>
<td>Leptin</td>
<td>Li et al., 2005</td>
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<tr>
<td>B65 cell line (dopamine neuron)</td>
<td>6-Hydroxydopamine</td>
<td>Kim et al., 2003</td>
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<td>SH-SY5Y (neuroblastoma cell line)</td>
<td>1-Methyl-4-phenylpyridinium</td>
<td>Kulich and Chu, 2001</td>
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ing cytochrome c release from mitochondria (Nowak, 2002). Thus, ERK1/2 may act on mitochondria to cause cytochrome c release and/or may regulate activation of caspase-3 downstream of cytochrome c release (Fig. 1).

ERK may act on mitochondria through Bax and/or p53. Bax is a member of the Bcl-2 family of proteins and acts as a proapoptotic molecule. During apoptosis induced by a variety of stimuli, Bax is translocated to the mitochondria, where it promotes the release of proapoptotic proteins from the intermembrane space (Degli Esposti and Dive, 2003). In renal epithelial and osteoblastic cells, Bax expression is increased after cisplatin or H$_2$O$_2$, and inhibition of the ERK pathway decreased Bax expression (Kim et al., 2005; Park et al., 2005). Similar to the role of ERK in the regulation of Bax expression, ERK activation is also associated with up-regulation of p53 expression in HeLa cells treated with shikonin (a red naphthoquinone pigment isolated from the ground rhizome of Lithospermum erythrorhizon) (Wu et al., 2005) and in lens epithelial cells treated with calcimycin, a calcium mobilizer (Li et al., 2005). In the presence of apoptotic stimuli, p53 has been reported to translocate to the mitochondria to inhibit the action of the antiapoptotic Bcl-x through the formation of a p53/Bcl-x complex (Petros et al., 2004) or to directly promote the proapoptotic activities of Bak (Mihara et al., 2003; Leu et al., 2004). Inhibition of Bcl-x and induction of Bax activity leads to cytochrome c release and caspase activation (Moll et al., 2005). In addition, ERK may regulate apoptosis via direct phosphorylation of p53. ERK can induce p53 phosphorylation at serine residue 15 (Persons et al., 2000), and inactivation of ERK resulted in p53 dephosphorylation and inhibited apoptosis (Brown and Benchimol, 2006). Together, these data suggest that Bax and p53 are important components in the ERK-mediated apoptotic signaling pathways (Fig. 1).

**ERK-Mediated Regulation of the Extrinsic Pathway**

ERK may induce apoptosis through regulation of the extrinsic apoptotic pathway. Jo et al. (2005) examined the effect of ERK inhibition on TNF-α expression and subsequent caspase-3 activation in cisplatin-induced acute renal failure in mice. They found that inhibiting ERK1/2 reduced TNF-α expression, caspase-3 activation, and apoptosis in kidney tissue, suggesting that ERK1/2 pathway may also participate in apoptosis by increasing an upstream signal for TNF-α production. It is established that increases in interleukin 1β (IL-1β) are closely associated with brain injury after cerebral ischemia (Barone and Feuerstein, 1999; Emsley and Tyrrell, 2002). Recently, Wang et al. (2004a) showed that cerebral ischemia in mice induces ERK activation and IL-1β expression, and inhibition of ERK activation by U0126 prevented increases in IL-1β mRNA. These studies implicate ERK-mediated expression of death ligands and proinflammatory cytokines as an important mechanism in exacerbating tissue injury (Fig. 1).

The extrinsic apoptotic pathway relies on the activation of an initial caspase, caspase-8. Cagnol et al. (2006) examined the effect of ERK pathway activation on caspase-8 and apoptosis in human embryonic kidney 293 cells that express an inducible form of Raf-1. They showed that prolonged ERK stimulation activated caspase-8 and potentiated Fas signaling and apoptosis, whereas expression of Bcl-X$_L$, an inhibitor of apoptosis, did not significantly alter the apoptotic rate (Cagnol et al., 2006). These data suggest that ERK can regulate the apoptotic pathway at the level of caspase-8 (Fig. 1).

**ERK-Mediated Suppression of Survival Signaling**

Promotion of cell death by ERK activation also may result from the suppression of survival signaling pathways. The phosphatidylinositol 3-kinase/Akt pathway plays a critical role in the regulation of cell survival, and most growth and survival factors activate this pathway (Amaravadi and Thompson, 2005). Recently, it was reported that withdrawal of soluble survival factors from primary cultures of mouse renal proximal tubular cells led to ERK1/2 activation that was accompanied by a gradual decrease in Akt activity and apoptosis (Sinha et al., 2004). Inhibition of ERK1/2 with U0126 or PD98059 in the cells deprived of survival factors not only prevented the decline in Akt activity but also resulted in cell survival (Sinha et al., 2004). These results support the idea that ERK1/2 activation in response to survival factor deprivation contributed to cell death via the suppression of the Akt pathway (Fig. 1). Although the precise mechanism by which ERK1/2 inhibits Akt remains unclear, ERK1/2 and Akt have been reported to coexist in a multimolecular complex containing at least ERK1/2, Akt, ribosomal S6 kinase 1, and phosphoinositide-dependent kinase 1 (Sinha et al., 2004). Whether ERK suppresses Akt activity through regulation of ribosomal S6 kinase 1 and phosphoinositide-dependent kinase 1 or through other signaling molecules requires further investigation.

**Upstream Inducers of ERK in Apoptosis**

ERK activation can be induced by different stimuli via distinct mechanisms. For example, Arany et al. (2004) reported that the EGF receptor mediates ERK activation, and inhibition of the EGF receptor blocked cisplatin-induced ERK activation and apoptosis in mouse renal proximal tubules. Likewise, Lee et al. (2005) showed that H$_2$O$_2$ triggers EGF receptor activation and that EGF receptor inactivation attenuated apoptosis in OK cells. Consequently, the death signal may initiate at a cellular membrane receptor and then propagate through an ERK-mediated signaling pathway.

Ras and Raf are downstream of growth factor receptors and mediate activation of MEK-ERK (Magnuson et al., 1994; Downward, 1998). Li et al. (2005) demonstrated that calcimycin-induced apoptosis of lens epithelial cells is mediated by MEK and ERK through a Ras and Raf-dependent pathway. Woessmann et al. (2002) showed that Ras-mediated activation of ERK by cisplatin induces cell death in osteosarcoma and neuroblastoma cell lines. In addition, calcium can induce ERK and apoptosis through a Ras-dependent and Raf-independent mechanism (Vossler et al., 1997; Li et al., 2005). Src also can transduce EGF receptor activation to ERK in cisplatin-induced apoptosis of mouse proximal tubular cells (Arany et al., 2004). In contrast, Sinha et al. (2004) reported that growth factor depletion-mediated cell death is dependent on ERK but not Raf. These data suggest that divergent intermediates are involved in transducing the death signal from the cellular membrane to ERK.

ROS play an important role in regulating cellular events, leading to ERK activation and subsequent apoptosis. In addition to exogenous ROS activation of ERK and apoptosis, cellular production of ROS—due to a stimulus—can result in ERK activation. For example, cisplatin-induced cytotoxicity
is closely related to increased generation of ROS (Sasada et al., 1996; Miyajima et al., 1997). ERK activation prompted by asbestos or the deprivation of growth factors can be blocked by the addition of ROS scavengers. Furthermore, H₂O₂ generation and ERK activation are involved in 2,3,5-tris(glu-tathion-S-yl)hydroquinone-induced cell death in LLC-PK1 cells (Tikoo et al., 2001; Ramachandiran et al., 2002; Dong et al., 2004). These studies suggest that ROS produce a specific environment that results in ERK-induced cell death.

**The Role of ERK5 in Apoptosis**

Studies examining the role of ERK in cell death have primarily relied upon MEK1 inhibitors U0126 and PD98059. Recently, it was reported that biological actions previously attributed to ERK1/2 may, in fact, be mediated by ERK5, a newer member of the MAPK family, because PD98059 and U0126 inhibit MEK1/2 as well as MEK5 (Kamakura et al., 1999; Cavanaugh et al., 2001). ERK5, also called big MAPK 1 or BMK1, contains a dual-phosphorylation motif (Thr-Glu-Tyr) similar to that in ERK1/2, and the N-terminal half of ERK5 shares sequence homology with other members of the MAPK family. However, a large C terminus and a unique loop-12 sequence distinguish it from ERK1/2. ERK5 is phosphorylated and activated by MEK5 but not by MEK1 or MEK2 (English et al., 1995; Zhou et al., 1995).

Similar to ERK1/2, activation of ERK5 plays a role in cell survival in response to a variety of stimuli, including oxidants and toxicants (Suzuki et al., 2002; Pi et al., 2004). Recently, ERK5 activation has been shown to promote apoptosis. For example, Sturla et al. (2005) reported that overexpression of ERK5 increased apoptosis in two medulloblastoma cell lines and primary cultures of patched heterozygous mouse medulloblastomas upon exposure to neurotrophin-3, whereas expression of small interfering RNA for the ERK5 activator, MEK5, inhibited neurotrophin-3-induced apoptosis. Furthermore, inhibition of myocyte enhancer factor 2, a specific target of ERK5, by a dominant-negative mutant of MEK5/ERK5-induced cell death (Sturla et al., 2005). Although ERK5 has an apparent role in cell death, the mechanisms for this are unclear. Because many stimuli that induce ERK1/2 activation also activate ERK5, it is tempting to speculate that the ERK5 pathway may also be involved in the death of other cell types.

**Conclusions and Future Directions**

Although ERK has generally been considered a survival signaling pathway, clear evidence exists that the ERK pathway mediates apoptosis induced by different stimuli in different tissues. The mechanisms by which ERK mediates apoptosis remain poorly understood and may occur at different levels. ERK1/2 may act upstream of mitochondria-mediated cytochrome c release and caspase-3 activation through up-regulation of Bax and p53 and through suppression of Akt-mediated survival signaling. Further studies are necessary to elucidate the activated signal transduction upstream and downstream of the cascades and to define the crosstalk among the cascades and other signaling pathways. The rationale for a signaling pathway being responsible for cell survival and apoptosis is not clear. At present, the signaling of survival or apoptosis by ERK seems to be dependent on the model system and injury paradigm. Furthermore, the kinetics and duration of ERK activation may play an important role in influencing its effect on cell fate. It has been reported that prolonged ERK activation is accompanied by the proapoptotic effect of ERK (di Mari et al., 1999), whereas a transient activation of ERK protects cells from death (Arany et al., 2004). Nevertheless, the protective effect of ERK inhibition has been reported in animal models of ischemia/reperfusion, and ERK activation was reported in humans who had experienced a stroke (Slevin et al., 2000); thus, the protection strategies that target these mechanisms merit further exploration.

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