Midkine Plays a Protective Role Against Cardiac Ischemia/Reperfusion Injury Through a Reduction of Apoptotic Reaction

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Background—Midkine (MK) is a heparin-binding growth factor involved in diverse biological phenomena, eg, neural survival, carcinogenesis, and tissue repair. MK could have a protective action against ischemia/reperfusion (I/R) injury in the heart, because MK was shown to have cytoprotective activity in cultured neurons and tumor cells. We investigated this hypothesis in mice with and without genetic MK deletion.

Methods and Results—Myocardial injury after I/R was produced by transient occlusion of coronary arteries. In wild-type (Mdk\textsuperscript{+/+}) mice, MK expression was increased after I/R in the periinfarct area. Infarct size/area at risk 24 hours after I/R in MK-deficient (Mdk\textsuperscript{−/−}) mice was larger than in Mdk\textsuperscript{+/+} mice (55.4±9.1% versus 32.1±5.3%, P<0.05). Terminal dUTP nick end-labeling–positive myocyte population in the periinfarct area in Mdk\textsuperscript{−/−} mice was higher than in Mdk\textsuperscript{+/+} mice (6.8±0.9% versus 3.2±0.6%, P<0.05). Left ventricular fractional shortening 24 hours after I/R in Mdk\textsuperscript{−/−} mice was significantly less than that in Mdk\textsuperscript{+/+} mice (34.3±4.4% versus 50.8±2.1%, P<0.05). Supplemental application of MK protein to left ventricle of Mdk\textsuperscript{−/−} mice at the time of I/R resulted in reduction of the infarct size. Application of exogenous MK to cultured cardiomyocytes resulted in increased Bcl-2 expression and decreased apoptosis after hypoxia/reoxygenation.

Conclusions—These results suggest that MK plays a protective role against I/R injury, most likely through a prevention of apoptotic reaction. MK is a potentially important new molecular target for treatment of ischemic heart disease. (Circulation. 2006;114:1713-1720.)

Key Words: apoptosis | myocardial infarction | reperfusion | signal transduction

Cardiomyocyte apoptosis is one of the major pathogenic mechanisms underlying myocardial ischemia and reperfusion (I/R) injury.\textsuperscript{1-3} Apoptosis indicates cell death and removal without the activation of an inflammatory process, based on DNA and cellular fragmentation. Activation of caspases is supposed to play a pivotal role in the genesis of apoptosis via activation of the endonucleases responsible for DNA degradation. Necrosis is a faster process, with early membrane failure, cellular swelling, and the release of cellular debris, which activates inflammation.\textsuperscript{4} This classification is becoming more obscure, however, because recent evidence has revealed that signaling processes for these 2 modes of cell death can switch with each other depending on the availability of high-energy phosphates.\textsuperscript{5,6} There is a continuum in the mode of cell death, with apoptosis on 1 end and necrosis at the other, and reperfusion leads to an increase in the rate of apoptosis. Apoptosis, which appears within 24 hours after I/R, would lead to decreased cardiac contractile performance and increased risk of heart failure through a direct massive loss of myocytes and induction of necrosis.\textsuperscript{7} Therefore, cardiac myocyte apoptosis may be a good target for therapeutic modulation in the context of myocardial infarction and I/R injury. Several strategies have been used to reduce apoptotic cell damage, including pharmacological and genetic interventions to modulate ion channels, nitric oxide (NO), growth factors, and downstream signaling molecules.\textsuperscript{4}

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Midkine (MK) is a heparin-binding growth factor with a molecular weight of 13 kDa, first isolated as the product of a retinoic acid–responsive gene in an embryonic carcinoma cell differentiation system; it is rich in basic amino acids and cysteine.\textsuperscript{5} Structurally, MK shares \textasciitilde50% sequence homology with pleiotrophin/heparin-binding growth-associated molecule...
but is not related to other growth factors or neurotrophic factors. MK is intensely expressed in many tissues during midgestation embryonic periods, whereas its expression in adult tissues is generally weak except in the kidney. MK has various biological activities: It promotes neurite outgrowth, survival of embryonic neurons, fibrinolytic activity of endothelial cells, and migration of inflammatory leukocytes. MK is expressed strongly in both early and advanced stages of tumors and is involved in carcinogenesis and tumor progression.9

MK could have a protective action against I/R injury of the heart through its antiapoptotic activity, because MK was shown to exert cytoprotective activity in Wilms’ tumor cells through enhancement of the expression of an antiapoptotic factor, Bcl-2,10 and to inhibit caspase-dependent cell damage via the activation of extracellular signal-regulated kinase (ERK) in cultured neurons.11 The present study was designed to test this hypothesis. We investigated the morphological and functional consequences of I/R insult in mice with and without genetic MK deletion, as well as the effects of supplementation with recombinant MK. In vitro experiments with cultured cardiomyocytes were also performed to shed light on the molecular signals involved. The data provide evidence that endogenous MK is cardioprotective and exogenous MK attenuates I/R injury, most likely by preventing the apoptotic reaction of cardiomyocytes.

Methods

Mouse Models

All animal experiments were performed in accordance with the regulations adopted by the National Institutes of Health and approved by the Animal Care and Use Committee of Nagoya University. Mice were supplied by the Department of Biochemistry, Nagoya University Graduate School of Medicine, Nagoya, Japan. MK-deficient (Mdk<sup>−/−</sup>) mice were generated as described elsewhere.12 Adult male wild-type C57BL/6 (Mdk<sup>+/+</sup>) and male Mdk<sup>−/−</sup> mice with the C57BL/6 genetic background were used in the I/R model (10 to 12 weeks old, weight 22 to 25 g) and were fed normal rodent chow. Mice were anesthetized with pentobarbital (100 mg/kg IP) and ventilated through a nose cone with a tidal volume of 0.2 mL at 120 breaths/min with a rodent respirator (model SN-480-7; Shinano, Tokyo, Japan). The extremity leads of the ECGs were monitored continuously. A thoracotomy was performed in the left third intercostal space, and the beating heart was exposed. An 8-0 polypropylene suture was passed under the left coronary artery at the inferior edge of the left atrium and tied with a slipknot to produce occlusion. Myocardial ischemia was verified by Blanching of the left ventricle (LV) and ST elevation in ECGs. After 60 minutes of ischemia, the left coronary artery occlusion was released by pulling on the slipknot. Air was then evacuated from the chest cavity, and the chest was closed with the ends of the slip outside of the incision. The ventilator was then removed, and normal respiration was restored. After 6 to 48 hours of reperfusion, animals were euthanized. Serum creatine phosphokinase (CPK) levels were measured in blood samples from mice at 24 hours after reperfusion. Serum CPK assays were performed by an outside laboratory (SRL, Tokyo, Japan).

Evaluation of Risk Area and Infarct Size

After 24 hours of reperfusion, mice were anesthetized and underwent a thoracotomy as described above. The heart was exposed, and the original suture, which remained in place, was retied. The heart was then perfused with 5% Evans blue (risk area), and area lacking TTC staining (infarct area) were measured by digital planimetry with a computer software program (Scion, Frederick, Md). Measurements from both sides of each slice were averaged. For each slice, the ratios of risk area to LV and infarct area to LV were determined and multiplied by the weight of the slice. These numbers of each slice were then summed over all slices, divided by the total weight of all slices, and multiplied by 100 to yield the risk area per LV and infarct area per LV for that heart as a percentage. Finally, the infarct area was calculated as a percentage of the risk area. All measurements and calculations were performed by a single individual who was blinded to genotype and treatment status.

Echocardiography

Transthoracic echocardiography was performed with a Nemio 20 (Toshiba Medical, Tokyo, Japan) to evaluate global cardiac function before and after I/R insult. Mice were lightly anesthetized with diethyl ether and placed in the supine position on a heating pad. The level of anesthesia was kept very light to maintain regular spontaneous respiration and to avoid compromising hemodynamic conditions. A 12-MHZ transducer was applied to the left hemithorax, and 2D targeted M-mode tracings were recorded. The data were analyzed by an observer blinded to mouse genotype.

MK Protein and Antibodies

Human recombinant MK protein was generated and purified as described previously.13 Monoclonal antibodies against mouse MK were raised by injection of the purified protein into rabbits and were refined by affinity chromatography on protein-A and MK columns. Antibodies were specific to MK and did not react with pleiotrophin/hearpin-binding growth-associated molecule.

Western Blotting Analysis

Western blot analysis was performed to evaluate MK protein levels in mouse LV tissue and to evaluate Bcl-2 and ERK-1/2 protein levels in cultured cardiomyocytes. For MK detection, LV tissue homogenates were subjected to sodium dodecyl sulfate (SDS)-polyacrylamide gel electrophoresis on a 15% polyacrylamide gel, and proteins were electroblotted on polyvinylidene fluoride membranes (Atto, Tokyo, Japan). For each picture, LV area excluding chamber, area lacking Evans blue (risk area), and area lacking TTC staining (infarct area) were measured by digital planimetry. For each picture, LV area excluding chamber, area lacking Evans blue (risk area), and area lacking TTC staining (infarct area) were measured by digital planimetry.
heparin-sepharose affinity chromatography as described previously. For immunolabeling of inflammatory cells, the section was stained with anti-mouse CD45 (leukocyte common antigen) antibody (Laboratory Vision Corporation, Fremont, Calif). Exposure to secondary antibody conjugated with goat anti-rat IgG (Jackson Laboratory) was followed by incubation with biotinyl-tyramide and streptavidin–horseradish peroxidase.

Cell Culture
Neonatal mouse ventricular myocytes were prepared from 1-day-old Institute of Cancer Research mice according to the manual of the Neonatal Cardiomyocyte Isolation System (Worthington, Lakewood, NJ). Briefly, ventricular pieces were incubated and stirred in Ca²⁺/Mg²⁺ free Hank’s balanced salt solution containing 100 U/mL collagenase at 37°C for 15 minutes. The cell suspension was collected, and the isolated cells were cultured in M199 medium (GIBCO BRL, Rockville, Md) with 10% fetal bovine serum, 5 μmol/L cytosine arabinoside, 50 U/mL penicillin, and 50 μg/mL streptomycin at 37°C in a humidified 5% CO₂/20% O₂ incubator. For hypoxia-reoxygenation (H/R) experiments, the hypoxic condition was created by incubating the cardiomyocytes in an anaerobic chamber equilibrated with 95% N₂ plus 5% CO₂ at 37°C for 6 hours. The myocytes were then returned to the former CO₂ incubator for reoxygenation. At the initiation of reoxygenation, the culture medium was changed to M199 with 0.5% fetal bovine serum, 5 μmol/L cytosine arabinoside, 50 U/mL penicillin, and 50 μg/mL streptomycin. Simultaneously, MK protein (100 ng/mL) was added to the altered culture medium for the MK treatment group. Cells were harvested at 18 hours after reoxygenation. To study the signaling pathways involved in the antiapoptotic action of MK in H/R, 20 μmol/L Bcl-2 inhibitor (Calbiochem, Darmstadt, Germany) or 50 μmol/L PD 98059 (Calbiochem) was added together with MK protein at the time of reoxygenation. In experiments in which ERK activity was measured, cultured myocytes were treated with 100 ng/mL MK protein for 30 minutes after 24 hours of serum starvation.

Detection of Apoptosis
Apoptotic myocardial cells were identified by terminal deoxynucleotidyl transferase (TdT)–mediated dUTP nick-end labeling (TUNEL) staining or by quantification of cytosolic oligonucleosome–bound DNA. For the TUNEL assay, deparaffinized LV tissue sections or cultured cardiomyocytes fixed by 4% paraformaldehyde in phosphate-buffered saline 3 times to remove DNA fragments were labeled with fluorescein-conjugated dUTP with terminal deoxynucleotidyl transferase (Roche Diagnostics Corp, Indianapolis, Ind). The total cell population was estimated by counting the Hoechst 33342–stained nuclei in 5 fields of each specimen using the 40× objective (total nuclei counted in each specimen were 5300 to 6100), and the ratio of TUNEL-positive cells to Hoechst 33342–stained nuclei in 5 fields of each sample using the 40× objective (total nuclei counted in each specimen were 5300 to 6100), and the ratio of TUNEL-positive cells to Hoechst 33342–stained nuclei was calculated. The DNA fragmentation of cultured cardiomyocytes was measured by quantification of cytosolic oligonucleosome–bound DNA with the Cell Death Detection ELISA kit (Roche Diagnostics Corp). Briefly, cardiomyocytes were rinsed with phosphate-buffered saline 3 times to remove nucleosomes that had leaked out from necrotic cells and then were incubated with the lysis buffer for 30 minutes. The supernatant containing nucleosomes from the cytosolic fraction of apoptotic cell was used as the antigen source in the sandwich ELISA with a primary antihistone antibody coated to the microtiter plate and a secondary anti-DNA antibody coupled to peroxidase.

Statistic Analysis
All values are expressed as mean±SEM. Statistical comparisons among the groups were performed by ANOVA with Bonferroni post hoc tests. Comparison between 2 groups were made with unpaired Student t test. Probability values of <0.05 were considered significant.

Results
MK Expression Is Increased in Mdk⁺/⁺ Mice Hearts After I/R
To examine the MK expression pattern in Mdk⁺/⁺ mice hearts after I/R, we subjected mice to 60 minutes of left coronary artery occlusion followed by 48 hours of reperfusion. We evaluated the time course of MK expression after I/R by Western blotting. Weak MK expression was recognized in control hearts, and the expression increased gradually through 6 to 12 hours. The strongest blotting band was shown after 24 hours and persisted as obviously expressed until 48 hours (Figure 1A and 1B). Next, we performed immunohistochemistry to detect localization of MK in heart sections of Mdk⁺/+ mice. Although only faint MK expression was recognized diffusely in control conditions (Figure 2A), MK was labeled strongly in the periinfarct region after I/R. The intensity of MK bands was analyzed by densitometry. Values are normalized to control. n=5. *P<0.01 vs control.

The authors had full access to the data and take full responsibility for its integrity. All authors have read and agree to the manuscript as written.

Myocardial Infarct Size Is Increased in Mdk⁻/⁻ Mice
We compared myocardial damage in Mdk⁺/+ and Mdk⁻/⁻ mice. The age and body weight of Mdk⁺/+ and Mdk⁻/⁻ mice were set to be identical. At baseline, there were no morphological differences between Mdk⁺/+ and Mdk⁻/⁻ hearts, and heart rate was identical. Although all mice survived the surgical induction of I/R, 32% (8/25) of Mdk⁻/⁻ mice died within 24 hours after I/R, whereas only 10% (4/40) of Mdk⁺/+ mice died during the same period (Figure 3A). In Western blotting, there was no obvious MK expression in Mdk⁻/⁻ mouse hearts 24 hours after
I/R (Figure 3B). To delineate area at risk (AAR) and infarct area, we stained the mouse hearts with Evans blue and TTC. Despite the fact that AAR was similar between Mdk+/+ and Mdk−/− mice, the extent of white necrotic area (infarct area) within the AAR of Mdk−/− mice was significantly larger than that of Mdk+/+ mice. Representative photomicrographs showing AAR and infarct area in Mdk+/+ and Mdk−/− mice 24 hours after I/R and summary data are presented in Figure 3C. We examined infiltration of inflam-
matory cells in the periinfarct area by immunostaining for CD45. The number of CD45-positive cells in Mdk⁻/⁻ mice was significantly larger than that in Mdk⁺/⁺ (Figure 3D). Although there was no significant difference in serum CPK activity between the sham-operated Mdk⁺/⁺ and Mdk⁻/⁻ mice, serum CPK activity of Mdk⁻/⁻ mice was significantly higher than that of Mdk⁺/⁺ mice at 24 hours after I/R (Figure 3E).

**Cardiac Function After I/R Is Preserved in Mdk⁺/⁺ Compared With Mdk⁻/⁻ Mice**

We investigated the morphological changes and left ventricular function of Mdk⁺/⁺ and Mdk⁻/⁻ mice. We performed echocardiography under light anesthesia so as to not compromise respiration and hemodynamic conditions. Before operation, there were no significant changes between Mdk⁺/⁺ and Mdk⁻/⁻ mice. The LV cavity was dilated, and LV fractional shortening (LVFS) was reduced immediately after I/R insults in both Mdk⁺/⁺ and Mdk⁻/⁻ mice; there was no statistical difference between the 2 animal groups. LVFS of Mdk⁺/⁺ mice was partially recovered, whereas LVFS of Mdk⁻/⁻ mice was further deteriorated; LVFS 24 hours after I/R in Mdk⁻/⁻ mice was significantly less than that in Mdk⁺/⁺ mice (Figures 4A and 4B).

**Increased Myocardial Apoptosis in Mdk⁻/⁻ Mice**

To investigate the extent of apoptosis in AAR, we performed TUNEL staining on the different experimental groups. The heart section obtained from the periinfarct area of Mdk⁻/⁻ mice exhibited a significantly larger number of TUNEL-positive myocytes than that of Mdk⁺/⁺ mice (Figures 5A and 5B). Autopsy results showed that 3 of 8 Mdk⁺/⁺ mice that died within 24 hours after I/R had intramyocardial hemorrhage, which reflected massive tissue destruction, whereas none of the 4 Mdk⁻/⁻ mice showed such myocardial tissue hemorrhage (data not shown).

**MK Protein Inhibits Apoptosis Through Bcl-2 and ERK Activation**

In experiments using cultured myocytes, we first investigated the cell-protective properties of exogenous MK using an H/R insult. To analyze DNA fragmentation, we examined nucleosomes measured by ELISA and TUNEL-positive cells. In myocytes isolated from Mdk⁺/⁺ mice, both the amount of nucleosome and the TUNEL-positive cell population after H/R significantly decreased by treatment with 100 ng/mL MK protein (Figures 6A and 6B).

We next compared the H/R-induced apoptosis in cardiomyocytes from Mdk⁺/⁺ and those from Mdk⁻/⁻ mice (Figure 6C). The TUNEL-positive cell population after H/R was significantly greater in cardiomyocytes from Mdk⁻/⁻ mice than in those from Mdk⁺/⁺ mice. The increase of the H/R-induced TUNEL-positive cell population in Mdk⁻/⁻ myocytes was reversed by application of exogenous MK protein (100 ng/mL). This indicates that both endogenous and exogenous MKs possess a considerable protective action against the H/R-induced apoptosis.

Because MK upregulates Bcl-2 activity in tumor cell lines, we investigated the influence of Bcl-2 expression by treatment
of exogenous MK protein in the H/R insult on cardiomyocytes from Mdk\(^{-/-}\) mice. Bcl-2 expression of ventricular myocytes after reoxygenation was upregulated with 100 ng/mL MK treatment, whereas there was no significant change between control and H/R without MK treatment (Figure 6D). Because activation of ERK is associated with cytoprotection in cardiomyocytes\(^{16}\) and directly mediates the upregulation of Bcl-2,\(^{17}\) we also analyzed ERK-1/2 phosphorylation in cultured cardiomyocytes. Under serum-starved conditions, the phosphorylation of ERK-1/2 was at a weak level, whereas the addition of 100 ng/mL MK significantly increased phosphorylated ERK-1/2 (Figure 6E). To verify the involvement of Bcl-2 and ERK in the signaling pathway for the antiapoptotic action of MK, we examined the effects of their respective inhibitors. In the presence of either an ERK inhibitor, PD 98059 (50 \(\mu\)mol/L), or a Bcl-2 inhibitor (20 \(\mu\)mol/L), MK protein treatment (100 ng/mL) did not cause a significant reduction of the TUNEL-positive cell population (Figure 6F).

**Exogenous MK Reduces Infarct Size in Mdk\(^{-/-}\) Mice**

We tested the therapeutic potential of MK for I/R injury. Using Mdk\(^{-/-}\) mice, we injected 20 \(\mu\)L MK protein (10 \(\mu\)g/mL) directly into the perinfarct area of LV free wall immediately after coronary reperfusion (MK-treated mice). In the control group, vehicle was given at the indicated time. Although AAR was similar, the infarct area within AAR of MK-treated mice was significantly smaller than that of the control group 24 hours after I/R (Figure 7A). Immunohistochemistry showed that a substantial amount of MK protein remained in the injected region 24 hours after I/R (Figure 7B).
Discussion

The present study demonstrates that MK plays a crucial role in the cardioprotection in response to I/R. Specifically, I/R resulted in upregulation of MK in Mdk−/− mice, with the highest expression in the perinfarct area at 24 hours after the insult. Furthermore, infarct size after I/R was larger and LV function after I/R was lower in Mdk−/− mice than in Mdk+/+ mice, and there was a greater degree of apoptosis in the perinfarct area in Mdk−/− mice than in Mdk+/+ mice. Supplemental in vivo MK application to LV of Mdk−/− mice at the time of I/R resulted in a reduction of infarct size. In vitro MK application to cardiomyocytes exhibited significant protective action against H/R-induced apoptosis in association with an enhancement of Bcl-2 expression and ERK activation. The in vitro action of exogenous MK was prevented by specific inhibitors of Bcl-2 and ERK. Taken together, these data suggest that MK exerts a protective effect against ischemic or hypoxic stress in cardiomyocytes, most likely through prevention of apoptosis.

Catheter-based and pharmacological reperfusion therapies are currently used in clinical practice to minimize cardiac damage after acute myocardial infarction. Prevention of apoptotic reaction in cardiomyocytes in the perinfarct zone is an alternative strategy. Several new experimental approaches have been reported recently. In a rat model of I/R injury, Nakamura et al18 provided evidence that endogenous hepatocyte growth factor is cardioprotective, and exogenous hepatocyte growth factor attenuates I/R injury through suppression of apoptosis in cardiomyocytes. Parsa et al19 reported that erythropoietin protected isolated cardiomyocytes from oxidative and hypoxic stress and protected in vivo rabbit hearts from myocardial infarction, possibly via its ability to activate cell survival pathways (Akt) and inhibit myocyte apoptosis. Other studies reported that adrenomedullin, a potent vasodilator, suppressed apoptosis of cardiomyocytes through activation of Bcl-2 signaling pathway, and its cardioprotective action against I/R injury was verified by adenoviral gene delivery to rat hearts.20 The G-actin sequestering peptide, thymosin β4, promotes myocardial and endothelial cell migration in embryonic heart and retains this property in postnatal cardiomyocytes. Bock-Marquette et al21 used a mouse model of myocardial infarction to demonstrate that thymosin β4 activated cell survival pathways, enhanced early myocyte survival, and improved cardiac function.

Certain biological functions of MK reported to date are mediated by its antiapoptotic action. These include a promotion of cell growth and an induction of oncogenic transformation.9,10,22 Thus, the antiapoptotic action of MK is widely involved in carcinogenesis, neurogenesis, and tissue repair. Candidates for the MK receptors are protein-tyrosine phosphatase-ζ, a chondroitin sulfate proteoglycan, and members of the low-density-lipoprotein receptor–related protein family.23,24 The downstream signaling systems of these receptors include ERK,25 which participates in the reduction of necrotic and apoptotic cell death.16 Therefore, induction of ERK by MK in the present study indicates that MK may prevent cardiomyocyte cell death in conjunction with the antiapoptotic effect via Bcl-2 enhancement.

MK is also known to promote the chemotaxis of neutrophils and the migration of macrophages. We have shown that MK has a critical role in neointima formation by enhancing the recruitment of inflammatory cells.13 In the present study, however, inflammatory cell numbers in the ischemic area of Mdk−/− mice were significantly greater than those of Mdk+/+ mice. In the ischemic myocardium, the benefit of antiapoptotic action of MK leading to a reduction of secondary necrosis, which activates inflammation, could offset the intrinsic proinflammatory reaction. Apoptosis in cardiac muscle may be more prone to shift to the necrosis, because the beating heart has higher energy requirements than other organs.5

Substantial controversy exists as to the role of inflammatory reaction in the progress of I/R injury of the heart.26–28 It is pointed out by some investigators that the evidence for its undesirable influence is equivocal.29,30 Indeed, antiinflammatory substances or leukocyte filters do not consistently prevent I/R injury and limit infarct size.31,32

We conclude that endogenous MK may primarily play a protective role against I/R injury of the heart, most likely through activation of antiapoptotic signaling pathways. Beneficial effects of exogenous MK to minimize I/R injury would provide a new perspective for innovation in the treatment of acute myocardial infarction.

Acknowledgments

We thank Drs H. Tsuchii and T. Murohara for critical advice and helpful discussion. We thank M. Hojo and T. Koike for technical assistance.

Sources of Funding

This work was supported by grants from the Ministry of Education, Culture, Sports, Science and Technology, Japan, and from the Suzuken Memorial Foundation, Japan (to Dr Horiba).
Apoptosis of cardiomyocytes is one of the major contributors to myocardial ischemia and reperfusion (I/R) injury. Because apoptosis appears within 24 hours after I/R and induces massive loss of myocytes, it will jeopardize cardiac function in the acute phase of myocardial infarction. A sequence of deteriorating events in the heart in response to myocardial infarction and I/R is, therefore, expected to be minimized if the apoptotic reaction in cardiomyocytes is prevented efficiently. This study addresses a novel protective action of midkine (MK) in the heart subjected to I/R. MK is a heparin-binding growth factor involved in diverse biological phenomena, eg, neural survival, carcinogenesis, and tissue repair. The study has shown a potent antiapoptotic effect of MK via the activation of Becl-2 and extracellular signal-regulated kinase in cardiomyocytes under ischemic and hypoxic stress in experiments with MK knockout mice and exogenous MK application. This novel cardioprotective effect of MK appears to limit infarct size by protecting myocardium in the ischemic zone, which leads to preservation of cardiac contractile function. Beneficial effects of exogenous MK to minimize I/R injury would provide a new perspective for innovation in the treatment of acute myocardial infarction.
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_Circulation_. 2006;114:1713-1720; originally published online October 2, 2006;
doi: 10.1161/CIRCULATIONAHA.106.632273
_Circulation_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2006 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
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