Research Article

A Novel Molecular Mechanism of IKKe-Mediated Akt/mTOR Inhibition in the Cardiomyocyte Autophagy after Myocardial Infarction

Shuai He,1,2 Jian Shen,3 Liangpeng Li,1 Yueyue Xu,1 Yide Cao,1 Li Yin,1 Zhonghao Tao,1 Zhibing Qiu,1 Wen Chen,1 and Xin Chen1

1Department of Thoracic and Cardiovascular Surgery, Nanjing First Hospital, Nanjing Medical University, Nanjing, Jiangsu 210006, China
2Department of Thoracic Surgery, Affiliated Hospital of Nantong University, Nantong, Jiangsu 226001, China
3Department of General Surgery, The Second Affiliated Hospital of Nanjing Medical University, Nanjing, Jiangsu 210011, China

Correspondence should be addressed to Wen Chen; cxacf@163.com and Xin Chen; stevecx@njmu.edu.cn

Received 6 February 2020; Revised 31 May 2020; Accepted 9 June 2020; Published 17 July 2020

Academic Editor: Fabio Altieri

Copyright © 2020 Shuai He et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Autophagy of cardiomyocytes after myocardial infarction (MI) is an important factor affecting the prognosis of MI. Excessive autophagy can lead to massive death of cardiomyocytes, which will seriously affect cardiac function. IKKe plays a crucial role in the occurrence of autophagy, but the functional role in MI remains largely unknown. To evaluate the impact of IKKe on the autophagy of cardiomyocytes after MI, MI was induced by surgical left anterior descending coronary artery ligation in IKKe knockout (KO) mice and wild-type (WT) mice. Starvation of H9c2 cells with IKKe siRNA and rescued with IKKe overexpressed afterwards to test the mechanism of IKKe in autophagy in vitro. Our results demonstrated that the expression of IKKe was upregulated in mice myocardial tissues which were consistent with cardiomyocyte autophagy after MI. Significantly, the IKKe KO mice showed increased infarct size, decreased viable cardiomyocytes, and exacerbated cardiac dysfunction when compared with the wild-type mice. Western blot and electron micrography analysis also revealed that loss of IKKe induces excessive cardiomyocyte autophagy and reduced the expression of p-Akt and p-mTOR. Similar results were observed in IKKe siRNA H9c2 cells in vitro which were under starvation injury. Notably, the levels of p-Akt and p-mTOR can restore in IKKe rescued cells. In conclusion, our results indicated that IKKe protects cardiomyocyte survival by reduced autophagy following MI via regulation of the Akt/mTOR signaling pathway. Thus, our study suggests that IKKe might represent a potential therapeutic target for the treatment of MI.

1. Introduction

Myocardial infarction (MI) was a major cause of death and disability throughout the world. After acute MI, the loss of cardiomyocyte triggers a host of molecular and cellular remodeling that initiates and subsequently modulates reparative responses including inflammation, hypertrophy, fibrosis, and the formation of a discrete collagen scar. Methods to inhibit cardiomyocyte death and increase cardiomyocyte survival can attenuate adverse remodeling and eventually improving cardiac function post-MI [1]. In the process of MI, the incomplete or complete occlusion of coronary arteries induced a potentially lethal shortage in the supply of oxygen and nutrients to cardiomyocytes [2]. Subsequently, efficient autophagic responses allow cardiomyocytes to cope with nutritional stress and maintain intracellular homeostasis, and may have considerable beneficial effects following ischemic insults [3]. Many studies indicated that autophagy mediates robust cardioprotective effects (such as anti-inflammatory, promotion of adaptation to stress, and support for cellular viability) in MI [4, 5]. Nevertheless, a growing number of evidences suggested that excessive or dysregulated autophagy contributed to the development of many cardiovascular disorders, especially MI [6, 7]. Therefore, it is of critical
importance to explore the autophagy mechanisms underlying MI and to develop novel therapeutic strategies that can effectively regulate this process.

The inhibitor of nuclear factor-κB (IκB) kinases ε (IKKe) was a key regulator of many biological events [8]. Evidence suggests that IKKe was required for the induction of the metabolic response of autophagy, which was not only typically associated with cell survival but also can cause cell death [9]. Recent studies have shown that IKKe can regulate the formation of autophagic vacuoles by regulating the phosphorylation level of the autophagy-associated receptor ALL0-1 [10], and IKKe also played an important regulatory role in the development of cardiovascular disease [11]. Until now, it remains unclear whether IKKe plays a role in the processes that occur after MI. Hence, the investigation of the pathophysiological contribution of cardiac IKKe expression to MI would provide valuable understanding on cardiac remodeling.

In the present study, the role and mechanism of IKKe in cardiomyocyte autophagy and cardiac function after MI were studied. We found that IKKe was a critical protective mediator in the process of cardiac remodeling after MI. Loss of IKKe induces excessive cardiomyocyte autophagy and reduced the expression of p-Akt and p-mTOR. And the levels of p-Akt and p-mTOR can be restored in IKKe rescued H9c2 cells under starvation injury. Our results indicated that IKKe protects cardiomyocyte survival by reduced autophagy following MI via regulation of the Akt/mTOR signaling pathway.

2. Materials and Methods

2.1. Animal Experiments. All animal procedures were performed in compliance with the Institute of Laboratory Animal Research Guide for the Care and Use of Laboratory Animals of the National Institutes of Health and approved by the Institutional Animal Care and Use Committee of Nanjing Medical University (Ethics Committee of Nanjing First Hospital). The IKKe KO mice (B6.Cg-Ikbmmt1Tman/J) were obtained from Jackson laboratory (Bar Harbor, ME, USA) and underwent rederivation to achieve pathogen-free status in the Model Animal Research Center of Nanjing University (Nanjing, China). For animals, IKKe KO mice with wild-type (WT) littermate (male; 8 to 12 weeks old; 26–30 g) were kept in a 12/12 h light/dark cycle, 25°C, with ad libitum access to food and water. MI was induced via permanent ligation of the left anterior descending (LAD) artery with a 6-0 Prolene suture for 28 days; in sham-operated animals, the same procedure was performed but without ligation. Specific details were performed as described previously [12].

2.2. Echocardiography and Micro-PET/CT. To evaluate the cardiac function, transthoracic echocardiography was performed using the Vevo 2100 echocardiogram (Visual Sonics, Canada) with a 10 MHz linear array ultrasound transducer. Mice were anesthetized by 1% to 2% isoflurane inhalation in a chamber. LV end-diastolic dimension (LVEDD), LV end-systolic dimension (LVEDd), and LV wall thickness were measured from M-mode images of echocardiography. Ejection fraction (EF) and fractional shortening (FS) were calculated. Echocardiographic measurements were taken from more than 3 separate mice of each group, and the sonographer was blinded to the information of the experimental group. Other specific details were performed as described previously [13].

Micro-PET/CT scanning for detection of viable myocardium was performed as previously described [14]. Mice were anesthetized by 1% to 2% isoflurane inhalation in a chamber for the 18F-FDG injection (tail vein) and placed back in the anesthesia cage. After 40 minutes, mice were anesthetized with ketamine 100 mg/kg and xylazine 10 mg/kg (injection volume, 100IL/10 g). Thereafter, the mice, with the heart centered in the tomograph, were symmetrically positioned on a warm bed with micropore tape, and a 15-minute static PET scan was performed, followed by a 7-minute CT scan.

2.3. Histological and Immunohistochemical Analysis. At different time points after surgery, mice were anesthetized intraperitoneally using sodium pentobarbital (100 mg/kg) and killed by swift decapitation according to the Guide for the Care and Use of Laboratory Animals published by the United States National Institutes of Health. The mouse hearts were fixed in 4% paraformaldehyde overnight at 4°C and then dehydrated through a graded ethanol series, cleared in xylenes, and embedded in paraffin wax. Samples were subsequently cut into 4 μM thick sections and stained with HE. For immunohistochemical studies, the sections were treated with 3% hydrogen peroxide for 15 min to block endogenous peroxidase activity. Then, sections were sealed with normal goat serum and incubated at 4°C with anti-IKKe antibody (1:200 dilution, Cell Signaling Technology #2690). The secondary antibody was horseradish peroxidase-(HRP-) conjugated goat anti-rabbit IgG (Beijing Zhongshan Biotechnology Co., Beijing, China). The signal was revealed by using a DAB Substrate Kit (Beijing Zhongshan Biotechnology Co.). Nuclei were counterstained with hematoxylin. Images were captured using an Olympus BX-URA2 camera with NIS-Elements D 3.2 software.

2.4. Transmission Electron Microscopy. Heart tissue was quickly cut into 1 mm cubes, fixed with 4% glutaraldehyde overnight at 4°C, fixed in 1% buffered osmium tetroxide, and then dehydrated in graded ethanol. Sections (60–70 nm) were double stained with 1% uranyl acetate and lead citrate and examined under a Hitachi H-7650 transmission electron microscope (FEI, Tecnai G2 Spirit Bio TWIN, USA).

2.5. Cell Culture and Lentivirus Infection. The rat embryonic cardiac myoblast H9c2 cells were purchased from the Cell Bank of the Chinese Academy of Sciences (Shanghai, China) and cultured in DMEM medium containing 10% fetal bovine serum (FBS, Gibco, Australia) and 1% antibiotic-antimycotic solution (100 U/mL penicillin and 100 μg/mL streptomycin) at 37°C in a 5% CO₂ incubator (Thermo, Waltham, MA, USA). For transfection, cells at 70% confluence were cultured in 6-well plates and infected with the lentiviral vector carrying anti-IKKe siRNA (siRNA IKKe); the target sequence used was GGTTGATGCTTCCAGGGT; the control group used empty lentiviral vector (siRNA control).

In the rescue experiment, IKKe was firstly knocked down in vitro by siRNA (siRNA IKKe) and the cells were
subsequently reinfected with LV-IKKε to overexpress IKKε (LV-IKKε) 72 h later. In the control group, the cells of siRNA IKKε were reinfected with negative control vectors (LV-control). The primers used for the vector of LV-IKKε were 5′-GAGGATCCCCGGGTACCGGTCGCCACCATGCGAGA GTACCCTAACTACCTG-3′; 5′-CTCTTGTAGTCCCAT ACCGACTTCTGGTGTGGAGAACATATTG-3′. The medium was replaced with DMEM 24 h later according to the manufacturer’s instructions. The efficiency of knockdown and reversal of IKKε in H9c2 cells was verified by western blot analysis. For starvation, the medium was replaced with DMEM without FBS to establish starvation cell model. The autophagy flux was blocked by adding 400 nM bafilomycin A1 (Baf, Selleck, USA) to the supernatant to incubate 4 h.

2.6. Cell ImmunoFluorescence. For immunofluorescent staining, cultured H9c2 cells were treated with the indicated lentivirus for 24 h and then starved for 8 h. Cells were grown on coverslips. Following stimulation, cells were fixed with 4% paraformaldehyde at room temperature followed by ethanol treatment at -20°C and washed with PBS. Then, cells were treated with 0.5% Triton X-100 and blocked in 5% goat serum.

2.7. Western Blotting Analysis. For western blotting, total protein was extracted from cardiac tissue and myocyte cells using a RIPA buffer and separated by SDS-PAGE, and the protein concentration was examined with a BCA protein assay kit (KGP902; Keygen, China). The proteins were transferred to polyvinylidene fluoride (PVDF) membranes (Millipore, Billerica, MA, USA) and blocked with 5% nonfat milk powder for 1 h. The membranes were probed with the following primary antibodies: anti-IKKε antibody (1:1000; Cell Signaling, #2690); anti-LC3 antibody (1:2000; Abcam, USA, #ab51520), anti-IKKε (1:200; Cell Signaling Technology, #2690), and goat anti-rabbit Alexa Fluor 488 (Fisher Scientific) and Alexa Fluor 568 phalloidin (Fisher Scientific). Images were acquired with a Nikon (C2+) confocal microscope.

3. Results

3.1. IKKε Expression Was Upregulated in the Murine Infarcted Hearts. To investigate the potential role of IKKε in the pathological processes that develop after MI, we first examined whether IKKε expression levels were altered in the diseased hearts. HE staining revealed myocardial derangement in the heart post-MI compared with the sham group (Figure 1(a)). Masson’s trichrome staining showed that myocardial fibrosis was significantly increased in the MI mice (Figure 1(a)). Compared with the control group, immunohistochemistry and western blot showed a gradual increase of IKKε expression in the mouse heart subjected to MI (Figures 1(a), 1(b), and 1(c)). Immunofluorescence staining also revealed that IKKε was colocated with troponin-marked cardiomyocytes in the ischemic myocardium (Figure 1(d)). Collectively, the alterations of IKKε levels in murine infarcted hearts indicate that IKKε may be involved in postinfarction cardiac dysfunction and ventricular remodeling.

3.2. IKKε Improved Cardiomyocyte Survival and Protected Cardiac Function Post-MI. A mouse model with WT and global knockout (KO) of IKKε (Figure 2(a)) were used with the sham or MI operation. All of the mice in the sham group were alive after surgery; 22 (70.9%) mice in the wild-type (WT) group and 18 (60%) mice in the KO group were survived until 28 days after MI, respectively. Compared with the WT group, KO mice showed higher mortality (Figure 2(b)). Echocardiography showed significant decrease of ejection fraction (EF) in KO mice post-MI (Figures 2(c) and 2(g)). We also observed that LV end-diastolic dimension (LVEDd) and LV end-systolic dimension (LVESd) of the heart in KO mice were higher and fractional shortening percentage (FS %) was lower when compared with WT mice post-MI (Figures 2(d), 2(e), and 2(f)). Additionally, viable myocardium was significantly reduced in KO mice, as compared with the control group 14 days after MI when tested by micropositron emission tomography/computed tomography (micro-PET/CT) (Figures 2(h) and 2(i)). Overall, these data provide evidence that the absence of IKKε in the heart increases postinfarction mortality, promotes cardiac dysfunction, and reduces viable myocardium following MI.

3.3. IKKε Reduced Excessive Autophagy in Cardiomyocytes after MI. Viable myocardium reduction is caused by the increase of cardiomyocyte death, and the disorder of autophagy is one of the important causes of cell death. Our research shows that autophagy peaked two weeks post-MI in the wild-type mice and the expression of IKKε also reached the highest value simultaneously (Figures 3(a) and 3(b)). To further verify the effect of IKKε in vivo, the expression of LC3 II/III, Beclin-1, and ATG-5 was examined in IKKε KO mice 2 weeks after MI. The results showed that LC3 II/III, Beclin-1, and ATG-5 were significantly upregulated in the mice of the IKKε KO group after MI (Figures 3(c) and 3(d)). And transmission electron microscopy analysis also demonstrated that the number of autophagic cardiomyocytes increased significantly in myocardial tissue of the IKKε KO mice (Figures 3(e) and 3(f)). The cell death genes (C-caspase 3,
Bax and anti-death protein (Bcl-2) were detected in myocardial tissue two weeks after MI. The expression of C-caspase 3 and Bax was increased, while the Bcl-2 was significantly reduced in IKKε KO mice when compared with the WT group (Figures 3(e) and 3(f)). Therefore, we speculate that IKKε may protect myocardial tissue by inhibiting excessive autophagy of cardiomyocytes after MI.

3.4. IKKε Prevented Cardiomyocytes from Starvation-Induced Excessive Autophagy In Vitro. The expression of IKKε was significantly increased in primary cultured mouse cardiomyocytes after starvation (Supplementary 1). Due to the difficulties in cell passage and low efficiency in transfection, the H9c2 cells were used for subsequent study in vitro. Given that cardiomyocyte autophagy could be induced at the initiation of MI due to the glycogen consumption, H9c2 cells were infected with IKKε-siRNA and exposed to starvation for 8 h (Figures 4(a) and 4(b)) to test the role of IKKε in cardiomyocyte autophagy. The knockdown of IKKε significantly increased the expression of LC3-II and ATG-5 (Figures 4(a) and 4(b)) after starvation. Western blot analyses also displayed that knockdown of IKKε in H9c2 cells promotes the expression of proteins Bax and cleaved caspase-3 but decreased the expression of protein Bcl-2 (Figures 3(a) and 3(b)). Moreover, the number of LC3 puncta stained by immunofluorescent was significantly increased in the siRNA-IKKε group than in the siRNA-control group (Figures 4(c) and 4(d)) in cells under starvation. In the siRNA-IKKε group, the autophagy flux was then blocked by Baf. The LC3-I/II was accumulated, and the apoptotic cells were subsequently reduced when compared with the cells without Baf (Supplementary 2). These results indicate the protective effects of IKKε under starvation injuries in H9c2 cells.

**Figure 1:** IKKε levels were increased in cardiomyocytes of the mouse postinfarction hearts. (a) Representative images of H&E staining, Masson staining, and immunohistochemical staining of IKKε transverse sections from a sham heart and an infarcted heart at 14 days after MI (n = 6 for each group; magnification, 200x). Scale bar represents 100 μm. (b, c) IKKε expression levels of the mouse hearts were detected via western blotting analysis (n = 5 per experimental group). ***P < 0.001. (d) Immunofluorescence staining images labeling IKKε (green) and troponin (red) in the border zones of MI mice at 14 days (n = 5 for each group; magnification, 200x). Scale bars represent 100 μm. Each experiment was repeated 3 times.
Figure 2: Continued.
3.5. IKKe Rescue Experiment in H9c2 Cells under Starvation Injury. To further validate the essential role of IKKe in cell autophagy, the rescue experiment with lentivirus over-IKKe and negative control vectors (over-control) was carried out in H9c2 cells. Western blot analyses displayed that the expression of IKKe in siRNA-IKKe and over-IKKe group cells was restored when compared with the siRNA-IKKe and over-control group. In addition, rescue of IKKe decreased autophagy proteins LC3II and ATG-5 expression (Figures 5(a) and 5(b)). Moreover, the number of LC3 puncta which was stained by immunofluorescent was also decreased in siRNA-IKKe and over-IKKe group cells (Figures 5(c) and 5(d)). By rescue, the expression of IKKe in H9c2 cells and proteins Bax and C-caspase-3 was decreased but the expression of protein Bcl-2 was increased after starvation (Figures 5(a) and 5(b)). In brief, these results indicated that IKKe may play an essential role in cell autophagy and thus lead to MI-induced cell death.

3.6. IKKe Mediates Post-MI Cardiomyocyte Autophagy through the Akt/mTOR Pathway. To explore the mechanism of IKKe that regulates excessive autophagy in cardiomyocytes, the autophagy-related signaling pathways were tested in vivo and in vitro. The total and phosphorylation levels ERK1/2, MEK1/2, Ikbα, and p38 did not change after IKKe was knocked down (Supplementary 3). Deficiency of IKKe in mouse significantly decreased the expression levels of p-Akt and p-mTOR compared with WT mice after MI (Figures 6(a) and 6(b)). Consistently, the expression of p-Akt and p-mTOR also showed a consistent downregulation when IKKe was knocked down by RNAi in vitro (Figures 6(c) and 6(f)). To further confirm the correlation between IKKe and Akt/mTOR expressions, rescue experiments in vitro were performed. Notably, in rescue cells, the levels of p-Akt and p-mTOR were also restored compared with control group cells (Figures 6(c) and 6(d)). Our results demonstrate that the IKKe-induced excessive autophagy upon MI is largely associated with the activation of AKT-mTOR signalings in the hearts.

4. Discussion and Conclusion

The present work was the first time to demonstrate the critical importance of IKKe in the development of MI, particularly cell autophagy. To investigate the potential function of IKKe in the development of MI and heart failure, a mouse model of MI by occluding the LAD coronary artery was established. Western blotting revealed that IKKe was significantly upregulated in cardiomyocytes and achieved the peak 14 days post-MI (Figures 1(a) and 1(b)) which just coincides with the time when cardiomyocytes start autophagy. To elucidate the role of IKKe in MI, a mouse MI model with a global knockout of IKKe was performed. The deficiency of IKKe increased MI-induced excessive autophagy of cardiomyocytes which results in several detrimental effects on the heart such as increased cardiomyocyte loss, infarct size, deteriorating LV functional, aggravated cardiac damage, and finally reduced survival post-MI cells. The lack of IKKe also leads to excessive autophagy in vitro. Autophagy was considered to play an important role in the elimination of cardiomyocyte post-MI, and the results mentioned above indicated that IKKe played an important regulatory role in autophagy.

Autophagy was a process of catabolism of cellular components and was necessary for the maintenance of cell homeostasis [15]. Efficient autophagic responses were considered to have beneficial effects post-MI, and many studies indicated that autophagy contributed etiologically to myocardial infarction [16, 17]. Matsui et al. reported that Becn1+/− mice—which were characterized by a partial autophagic defect at the whole-body level—were more resistant to cardiac damage at reperfusion than their WT controls [7]. However, abnormal autophagy was proven to be associated with cardiovascular diseases [18]. The process of autophagy of cardiomyocytes has the bidirectional regulation effect of maintaining cell survival or inducing cell death, that is, an appropriate level of autophagy can maintain the steady state of cardiomyocytes, while excessively activated autophagy can cause cardiomyocyte death and cause serious consequences. Therefore, autophagy plays an essential role...
**Figure 3:** Loss of IKKe induced excessive autophagy and increased apoptosis in cardiomyocytes after MI. (a, b) LC3II, Beclin-1, and ATG-5 expression levels of the mouse hearts after MI were detected via western blotting analysis (n = 5 per experimental group). **P < 0.01, ***P < 0.001. (c, d) Representative western blots and quantitative results of IKKe, LC3II, ATG-5, C-caspase 3, Bcl-2, and Bax in WT and KO mice at 2 weeks after MI or sham operation (n = 5 for each group). **P < 0.01, ***P < 0.001. (e) Representative electron micrographs showing cardiomyocyte autophagy in the border zone of the WT and KO hearts at 2 weeks after MI (n = 5-6 for each group). Scale bar represents 1 nm. (f) The quantification of autophagy is expressed as a percentage of autophagic vacuole area. **P < 0.01. Each experiment was repeated 3 times.
in the occurrence of cardiovascular disease [19]. Similarly, the present study showed that loss of IKKε induced excessive autophagy in cardiomyocyte post-MI which resulted in aggravated cardiac damage.

It has been well documented that ischemia leads to a sudden increase of cardiomyocyte apoptosis [20] and caused collective loss of cardiomyocytes throughout the entire pathological process post-MI [21]. Accordingly, the inhibition of cardiomyocyte apoptosis showed potential protection against post-MI cardiac dysfunction and limited infarct size [22]. Mitochondria acted as central regulators of apoptosis when they received stress signals, such as starvation, hypoxia, oxidative stress, and DNA damage from cardiomyocytes [23]. The permeability of mitochondrial membrane was regulated by a family of proteins known as the Bcl-2 family, which includes antiapoptotic (Bcl-2) and proapoptotic (Bax, Bid, Bak, etc.) [24]. Consistently, the present study revealed that lack of IKKε would increase cardiomyocyte death and apoptosis in the ischemic heart by inducing caspase-3 and Bax and inhibiting Bcl-2 activity both in vivo (Figures 2(e) and 2(f)) and in vitro (Figures 3(a) and 3(b)). These results suggested that IKKε might mediated cardiomyocyte apoptosis.
via the mitochondrial apoptosis pathway. Moreover, previous evidences have showed the antiapoptosis effect of IKKε in different types of cells. Renner et al. reported that IKKε accumulates in subnuclear promyelocytic leukemia (PML) bodies upon genotoxic stress, where it undergoes SUMOylation, leading to its activation and ultimately resulting in NF-κB-mediated antiapoptotic responses [25]. Additionally, several glioma cell lines and human primary glioma tissues exhibit elevated levels of IKKε and were less sensitive to DNA damage-induced apoptosis [26], whereas suppression of IKKε leads to cells becoming more sensitive, which were also consistent with our experimental findings [27].

The present study suggested that IKKε might play a protective role on cardiomyocyte survival post-MI while its molecular mechanisms remained unclear. The Akt/mTOR pathway was a major signal transduction pathway which is responsible for regulating cell proliferation, survival, autophagy, and apoptosis. This study displayed that IKKε-mediated

**Figure 5:** IKKε is essential for H9c2 cell survival under starvation injury. H9c2 cells were infected with siRNA-control and LV-control, siRNA-IKKε and Over-control, and siRNA-IKKε and Over-IKKε three groups with or without starvation injury, a total of 6 groups. (a, b) Representative western blots and quantitative results of IKKε, LC3I/II, ATG-5, C-caspase 3, Bcl-2, and Bax in H9c2 cells of each 6 groups. *P < 0.05; **P < 0.01; ***P < 0.001. (c) Representative immunofluorescent staining of LC3 in H9c2 cells of each 6 groups (n = 4 for each group; magnification, 600x). Scale bar represents 10 μm. (d) The quantification of autophagy is expressed as the number of LC3 puncta per area (n = 4 for each group). **P < 0.01.
Figure 6: IKKε mediates cardiomyocyte autophagy through the Akt/mTOR pathway. (a, b) Representative western blots and quantitative results of phosphorylation and total protein levels of AKT and mTOR in WT and KO mice at 2 weeks after MI or sham operation (n = 5 for each group). **P < 0.01, ***P < 0.001. (c, d) Representative western blots and quantitative results of phosphorylation and total protein levels of AKT and mTOR in H9c2 cells under starvation injury. *P < 0.05, **P < 0.01, ***P < 0.001. (e, f) Representative western blots and quantitative results of phosphorylation and total protein levels of AKT and mTOR in H9c2 cells after the rescue of IKKε.
post-MI cardiomyocyte death was largely dependent on the inhibition of the Akt/mTOR signaling pathways both in vivo and in vitro (Figure 6). The mTOR was a master regulator of several crucial cellular processes, including protein synthesis, cellular growth, proliferation, autophagy, lysosomal function, and cell metabolism [28, 29]. The mTOR pathway regulated both physiological and pathological processes in the cardiovascular system. Partial or selective inhibition of mTOR conferred cardioprotection in multiple cardiac pathological conditions [30]. As revealed in this study, the deficiency of IKKε significantly inhibited the expression levels of p-Akt and p-mTOR and subsequently leading to cardiomyocyte death and deterioration of cardiac function when compared with control group both in vivo and in vitro. Eventually, rescuing IKKε by overexpression in vitro could partially restore the expression of p-Akt and p-mTOR levels. Similar evidences were also reported that IKKε might promote cell survival by directly phosphorylating Akt [31, 32]. One limitation of this research was that the results of MI remodeling in vivo were based on a global knockout of IKKε and we could not guarantee that IKKε deficiency of other cell types might have contributed to the observed effects on the heart. In addition, we used rat embryonic cardiac myoblasts (H9c2 cells) instead of cardiomyocytes isolated form the heart. In embryonic mice in the in vitro experiments which may account for some differences.

In summary, this study presents the first evidence that IKKε was a critical protective mediator in the process of cardiac remodeling in response to MI. The deficiency of IKKε would cause excessive autophagy of cardiomyocyte and eventually lead to exacerbate infarct size expansion and deteriorate cardiac function post-MI. Therefore, we propose that targeting IKKε is a promising approach for preventing or treating MI.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Authors’ Contributions

Shuai He, Jian Shen, and Liangpeng Li contributed equally to this work.

Acknowledgments

This study was supported by grants from the Young Program of the National Natural Science Foundation of China (No. 81700415) and (No. 81870193).

Supplementary Materials

Supplementary 1. IKKε increased in primary cardiac myocytes under starvation injury. Supplementary 2. Knockdown of IKKε activated the entire autophagy flux and blocking the autophagy flux by Baf reduced apoptosis in H9c2 cells under starvation injury. Supplementary 3. IKKε did not change the phosphorylation levels of ERK1/2, MEK1/2, Ikβα, and p38. (Supplementary Materials)

References

[1] F. G. Spinale, J. S. Janicki, and M. R. Zile, "Membrane-associated matrix proteolysis and heart failure," Circulation Research, vol. 112, no. 1, pp. 195–208, 2013.
[2] S. Arman, O. Vyacheslav, N. Talgat et al., "Role of the immune system in cardiac tissue damage and repair following myocardial infarction," Inflammation Research, vol. 66, no. 9, pp. 739–751, 2017.
[3] C. He, M. C. Bassik, V. Moresi et al., "Exercise-induced BCL2-regulated autophagy is required for muscle glucose homeostasis," Nature, vol. 481, no. 7382, pp. 511–515, 2012.
[4] D. A. Kubli, X. Zhang, Y. Lee et al., "Parkin protein deficiency exacerbates cardiac injury and reduces survival following myocardial infarction," The Journal of Biological Chemistry, vol. 288, no. 2, pp. 915–926, 2013.
[5] Y. Maejima, S. Kyoizumi, P. Zhai et al., "Mst1 inhibits autophagy by promoting the interaction between Beclin1 and Bcl-2," Nature Medicine, vol. 19, no. 11, pp. 1478–1488, 2013.
[6] X. Liu, Y. Deng, X. Xu, W. Jin, and H. Li, "MicroRNA-223 protects neonatal rat cardiomyocytes and H9c2 cells from hypoxia-induced apoptosis and excessive autophagy via the Akt/mTOR pathway by targeting PARP-1," Journal of Molecular and Cellular Cardiology, vol. 118, pp. 133–146, 2018.
[7] Y. Matsui, H. Takagi, X. Qu et al., "Distinct roles of autophagy in the heart during ischemia and reperfusion: roles of AMP-activated protein kinase and Beclin 1 in mediating autophagy," Circulation Research, vol. 100, no. 6, pp. 914–922, 2007.
[8] J. Zhang, M. Tian, Z. Xia, and P. Feng, "Roles of IκB kinase ε in the innate immune defense and beyond," Virologica Sinica, vol. 31, no. 6, pp. 457–465, 2016.
[9] S. Yang, Y. Imamura, R. W. Jenkins et al., "Autophagy inhibition dysregulates TBK1 signaling and promotes pancreatic inflammation," Cancer Immunology Research, vol. 4, no. 6, pp. 520–530, 2016.
[10] M. Sato, K. Sato, K. Tomura, H. Kosako, and K. Sato, "The autophagy receptor ALLO-1 and the IKKE-1 kinase control clearance of paternal mitochondria in Caenorhabditis elegans," Nature Cell Biology, vol. 20, no. 1, pp. 81–91, 2018.
[11] C. Cao, Y. Zhu, W. Chen et al., "IKKε knockout prevents high fat diet induced arterial atherosclerosis and NF-κB signaling in mice," PLoS One, vol. 8, no. 5, article e64930, 2013.
[12] Y. Cao, S. He, Z. Tao et al., "Macrophage-specific IκB kinase α contributes to ventricular remodelling and dysfunction after myocardial infarction," The Canadian Journal of Cardiology, vol. 35, no. 4, pp. 490–500, 2019.
[13] D.-S. Jiang, L. Li, L. Huang et al., "Interferon regulatory factor 1 is required for cardiac remodeling in response to pressure overload," Hypertension, vol. 64, no. 1, pp. 77–86, 2014.
[14] A. Greco, M. P. Petretta, M. Larobina et al., "Reproducibility and accuracy of non-invasive measurement of infarct size in mice with high-resolution PET/CT," Journal of Nuclear Cardiology, vol. 19, no. 3, pp. 492–499, 2012.
[15] J. D. Rabinowitz and E. White, "Autophagy and metabolism," Science, vol. 330, no. 6009, pp. 1344–1348, 2010.
[16] G. Chen, Z. Han, D. Feng et al., “A regulatory signaling loop comprising the PGAM5 phosphatase and CK2 controls receptor-mediated mitophagy,” Molecular Cell, vol. 54, no. 3, pp. 362–377, 2014.

[17] W. Lu, J. Sun, J. S. Yoon et al., “Mitochondrial protein PGAM5 regulates mitophagic protection against cell necroptosis,” PLoS One, vol. 11, no. 1, article e0147792, 2016.

[18] J. H. Lee, W. H. Yu, A. Kumar et al., “Lysosomal proteolysis and autophagy require presenilin 1 and are disrupted by Alzheimer-related PS1 mutations,” Cell, vol. 141, no. 7, pp. 1146–1158, 2010.

[19] J. M. Bravo-San Pedro, G. Kroemer, and L. Galluzzi, “Autophagy and mitophagy in cardiovascular disease,” Circulation Research, vol. 120, no. 11, pp. 1812–1824, 2017.

[20] M. Prech, A. Marszalek, J. Schröder et al., “Apoptosis as a mechanism for the elimination of cardiomyocytes after acute myocardial infarction,” The American Journal of Cardiology, vol. 105, no. 9, pp. 1240–1245, 2010.

[21] G. W. Dorn II, “Apoptotic and non-apoptotic programmed cardiomyocyte death in ventricular remodelling,” Cardiovascular Research, vol. 81, no. 3, pp. 465–473, 2008.

[22] Y. Chandrashekhar, S. Sen, R. Anway, A. Shuros, and I. Anand, “Long-term caspase inhibition ameliorates apoptosis, reduces myocardial troponin-I cleavage, protects left ventricular function, and attenuates remodeling in rats with myocardial infarction,” Journal of the American College of Cardiology, vol. 43, no. 2, pp. 295–301, 2004.

[23] R. A. Gottlieb, “Mitochondrial signaling in apoptosis: mitochondrial daggers to the breaking heart,” Basic Research in Cardiology, vol. 98, no. 4, pp. 242–249, 2003.

[24] R. J. Youle and A. Strasser, “The BCL-2 protein family: opposing activities that mediate cell death,” Nature Reviews Molecular Cell Biology, vol. 9, no. 1, pp. 47–59, 2008.

[25] F. Renner, R. Moreno, and M. L. Schmitz, “SUMOylation-dependent localization of IKKε in PML nuclear bodies is essential for protection against DNA-damage-triggered cell death,” Molecular Cell, vol. 37, no. 4, pp. 503–515, 2010.

[26] H. Guan, H. Zhang, J. Cai et al., “IKBKE is over-expressed in glioma and contributes to resistance of glioma cells to apoptosis via activating NF-κB,” The Journal of Pathology, vol. 223, no. 3, pp. 436–445, 2011.

[27] K. Verhelst, L. Verstrepen, I. Carpentier, and R. Beyaert, “IκB kinase ε (IKKe): a therapeutic target in inflammation and cancer,” Biochemical Pharmacology, vol. 85, no. 7, pp. 873–880, 2013.

[28] S. Sciarretta, M. Volpe, and J. Sadoshima, “Mammalian target of rapamycin signaling in cardiac physiology and disease,” Circulation Research, vol. 114, no. 3, pp. 549–564, 2014.

[29] R. A. Saxton and D. M. Sabatini, “mTOR signaling in growth, metabolism, and disease,” Cell, vol. 168, no. 6, pp. 960–976, 2017.

[30] S. Sciarretta, M. Forte, G. Frati, and J. Sadoshima, “New insights into the role of mTOR signaling in the cardiovascular system,” Circulation Research, vol. 122, no. 3, pp. 489–505, 2018.

[31] J. P. Guo, D. Coppola, and J. Q. Cheng, “IKBKE protein activates Akt independent of phosphatidylinositol 3-kinase/PDK1/mTORC2 and the pleckstrin homology domain to sustain malignant transformation,” Journal of Biological Chemistry, vol. 291, no. 43, article 22853, 2016.

[32] X. Xie, D. Zhang, B. Zhao et al., “IκB kinase ε and TANK-binding kinase 1 activate AKT by direct phosphorylation,” Proceedings of the National Academy of Sciences, vol. 108, no. 16, pp. 6474–6479, 2011.