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RESEARCH PAPER

IL-21 promotes myocardial ischaemia/reperfusion injury through the modulation of neutrophil infiltration

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BACKGROUND AND PURPOSE

The immune system plays an important role in driving the acute inflammatory response following myocardial ischaemia/reperfusion injury (MIRI). IL-21 is a pleiotropic cytokine with multiple immunomodulatory effects, but its role in MIRI is not known.

EXPERIMENTAL APPROACH

Myocardial injury, neutrophil infiltration and the expression of neutrophil chemokines KC (CXCL1) and MIP-2 (CXCL2) were studied in a mouse model of MIRI. Effects of IL-21 on the expression of KC and MIP-2 in neonatal mouse cardiomyocytes (CMs) and cardiac fibroblasts (CFs) were determined by real-time PCR and ELISA. The signalling mechanisms underlying these effects were explored by western blot analysis.

KEY RESULTS

IL-21 was elevated within the acute phase of murine MIRI. Neutralization of IL-21 attenuated myocardial injury, as illustrated by reduced infarct size, decreased cardiac troponin T levels and improved cardiac function, whereas exogenous IL-21 administration exerted opposite effects. IL-21 increased the infiltration of neutrophils and increased the expression of KC and MIP-2 in myocardial tissue following MIRI. Moreover, neutrophil depletion attenuated the IL-21-induced myocardial injury. Mechanistically, IL-21 increased the production of KC and MIP-2 in neonatal CMs and CFs, and enhanced neutrophil migration, as revealed by the migration assay. Furthermore, we demonstrated that this IL-21-mediated increase in chemokine expression involved the activation of Akt/NF-κB signalling in CMs and p38 MAPK/NF-κB signalling in CFs.

CONCLUSIONS AND IMPLICATIONS

Our data provide novel evidence that IL-21 plays a pathogenic role in MIRI, most likely by promoting cardiac neutrophil infiltration. Therefore, targeting IL-21 may have therapeutic potential as a treatment for MIRI.

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LINKED ARTICLES
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Abbreviations
AMI, acute myocardial infarction; CF, cardiac fibroblast; CM, cardiomyocyte; KC, keratinocyte-derived chemokine (CXCL1); MIP-2, macrophage inflammatory protein-2 (CXCL2); MIRI, myocardial ischaemia/reperfusion injury; STAT, signal transducers and activators of transcription

Introduction

Acute myocardial infarction (AMI) is one of the leading causes of death worldwide. Early reperfusion after coronary artery occlusion is the most effective strategy to protect the vulnerable myocardium and limit infarct size. However, a variety of alterations occurring at the time of blood flow restoration may paradoxically exert deleterious effects and result in additional injury, which is referred to as myocardial ischaemia/reperfusion injury (MIRI). Numerous pathophysiological mechanisms are involved in MIRI, including calcium overload, disturbances of the mitochondrial membrane potential, free radical formation, endothelial dysfunction, platelet aggregation and microembolization (Turer and Hill, 2010). Furthermore, there is a growing appreciation of the role activation of the immune system plays in the pathogenesis of myocardial damage after reperfusion (Timmers *et al.*, 2012; Hofmann and Frantz, 2015).

IL-21 is a type-I cytokine produced primarily by $CD4^+$ T-cell populations and natural killer (NK) T-cells, as well as by $CD8^+$ T-cells and gamma delta (γδ) T-cells (Sutton *et al.*, 2009; Spolski and Leonard, 2014). IL-21 exerts broad immunomodulatory effects and is involved in antitumour and antiviral responses, as well as in inflammatory responses, where it promotes the development of autoimmune diseases and certain inflammatory disorders (Parrish-Novak *et al.*, 2000; Spolski and Leonard, 2008). IL-21 signals through a heterodimeric receptor complex formed by its unique receptor **IL-21 receptor and the common cytokine receptor γ chain, γ_c**. The IL-21 receptor is widely expressed by immune cells, including T-cells, B cells, NK cells, NKT-cells, dendritic cells, macrophages and neutrophils (Spolski and Leonard, 2014). More recently, the expression of IL-21 receptors was also demonstrated in non-immune cells, such as epithelial cells (Caruso *et al.*, 2007a,b), fibroblasts (Jungel *et al.*, 2004; Monteleone *et al.*, 2006), keratinocytes (Distler *et al.*, 2005; Caruso *et al.*, 2009), endothelial cells (Wang *et al.*, 2015) and neurons (Tzartos *et al.*, 2011; Clarkson *et al.*, 2014), suggesting the possibility that IL-21 may modulate additional inflammatory pathways besides its regulatory effects on humoral and cellular immunity. Recent findings suggest an early elevation of IL-21 following liver IRI in mice, which may be partially responsible for NK cell-mediated liver injury (Feng *et al.*, 2012). Clarkson *et al.* reported that in a mouse model of transient focal brain ischaemia, IL-21 was highly up-regulated in ischaemic brain tissues and played a pathogenic role (Clarkson *et al.*, 2014). However, potential implications of IL-21 in relation to MIRI are still far from complete.

In this study, we demonstrated that IL-21 was elevated during the acute phase following MIRI. $CD4^+$ T-cells were a major source of IL-21 production. Neutralization of endogenous IL-21 protected against myocardial injury, whereas exogenous IL-21 administration aggravated myocardial injury. IL-21 increased the infiltration of neutrophils following MIRI and increased myocardial expression of CXC chemokines **keratinocyte-derived chemokine (KC, also known as CXCL1)** and **macrophage inflammatory protein-2 (MIP-2, also known as CXCL2)**. Depletion of neutrophil attenuated the IL-21-induced myocardial injury. Furthermore, IL-21 directly increased the expression of KC and MIP-2 in cardiomyocytes (CMs) and cardiac fibroblasts (CFs) *in vitro*. The potential signalling mechanisms underlying these responses may involve the **Akt**, **p38 MAPK** and NF-κB signalling pathways.

Methods

Animal model and treatments

Animal studies are reported in accordance with the ARRIVE guidelines (Kilkenny *et al.*, 2010; McGrath and Lilley, 2015). Male C57BL/6 mice aged 8–12 weeks (weight 20–24 g) were purchased from Wuhan University (Wuhan, China) and maintained on a chow diet in a 12 h light/12 h dark environment at 25°C in the Tongji Medical School Animal Care Facility. The treatment and care of the animals were approved by the Animal Care and Utilization Committee of Huazhong University of Science and Technology. The experimental procedures used in the work were as humane as possible. A murine MIRI model was established by temporary occlusion of the left anterior descending (LAD) coronary artery as previously described (Michael *et al.*, 1995; Tarnavski *et al.*, 2004; Bohl *et al.*, 2009). Briefly, mice were anesthetized by intraperitoneal injection of ketamine (50 $mg{\cdot}kg^{-1}$) and pentobarbital sodium (50 $mg{\cdot}kg^{-1}$) and ventilated through a rodent respirator. The adequacy of anaesthesia was assessed by testing corneal reflexes and motor responses to tail pinch. Hearts were exposed by left thoracotomy, and the LAD coronary artery was visualized and ligated using 6-0 suture around fine PE-10 tubing with a slip knot. Sham-operated animals were subjected to the same surgical procedures without LAD artery ligation.

For the measurement of IL-21/IL-21 receptor expression patterns, C57BL/6 mice were randomly subjected to a sham procedure or to 30 min of ischaemia followed by 30 min or 1, 6, 12 or 24 h of reperfusion (n = 6 per group). To elucidate the causative role of IL-21 in this process, mice were randomly

assigned to four groups. In the (1) anti-IL-21 treatment group (anti-IL-21, n = 9) and the (2) isotype control antibody treatment group (isotype, n = 9), mice were injected i.v. with 100 μg of anti-IL-21 neutralizing mAb or an isotype control mAb 5 min prior to reperfusion. In the (3) recombinant mouse-IL-21 treatment group (IL-21, n = 10) and the (4) vehicle treatment group (vehicle, n = 11), mice were injected i.v. with 1 μg of recombinant mouse IL-21 diluted in PBS or PBS containing 0.5% BSA 5 min prior to reperfusion. For the neutrophil depletion study, the mice were randomly divided into five groups: (1) the PBS treatment group (n = 5); (2) the isotype control mAb treatment group (n = 5); (3) the anti-Ly6G mAb treatment group (n = 5); (4) the isotype control mAb with IL-21 treatment group (n = 5); and (5) the anti-Ly6G mAb with IL-21 treatment group (n = 5). In these groups 250 μg of isotype control mAb or anti-Ly6G mAb was injected i.p. 1 day before surgery; 1 μg of recombinant mouse IL-21 was injected i.v. 5 min prior to reperfusion.

Echocardiographic analysis of cardiac function

At the end of a 1 day reperfusion period, mice were anaesthetized with inhaled 2% isoflurane/oxygen mixture and two-dimensional echocardiographic views of the mid-ventricular short axis, and the parasternal long axes were obtained using a Vevo 2100 high-resolution microimaging system (VisualSonics, Toronto, Ontario, Canada) by a technician who was blinded to treatment groups. Left ventricular ejection fraction (EF) and fractional shortening (FS) were calculated from the digital images using a standard formula as described previously (Li *et al.*, 2007).

Serum troponin T

Blood concentrations of troponin T (cTnT) were measured as an index of cardiac cellular damage using a quantitative rapid assay kit (Roche Diagnostics GmbH, Mannheim, Germany) as described previously (Metzler *et al.*, 2001).

Measurement of area at risk and infarct size

Infarct size after MIRI was determined as described previously (Michael *et al.*, 1995; Bohl *et al.*, 2009). Briefly, after 24 h of reperfusion, mice were anaesthetized and the LAD coronary artery was re-occluded at the previous ligation. Evans blue dye (1%) was injected, and the heart was quickly excised, frozen and cut into transverse sections below the ligature. These sections were then incubated with 1% 2,3,5-triphenyltetrazolium chloride (TTC) solution. Left ventricular (LV) area, area at risk and infarct area were analysed as described previously (Bohl *et al.*, 2009) using Image-Pro Plus 6.0 software. The measurement was carried out by an investigator who was blinded to the experimental groups.

Isolation of heart-infiltrating cells and flow cytometry analysis

Leukocytes that had infiltrated the heart were isolated as described previously, with some modifications (Liao *et al.*, 2012). Briefly, after the animals had been killed by cervical dislocation, ischaemic tissue was excised and single-cell suspensions were obtained via the digestion of ischaemic myocardium with 0.1% collagenase B solution. Thereafter, granulocytes were concentrated through density gradient centrifugation using Ficoll (Histopaque-1119). For the analysis of neutrophil infiltration in ischaemic tissue, the cells were labelled with PE-cy7 anti-mouse CD11b and PE anti-mouse Ly-6G/Gr-1. For the analysis of IL-21-secreting leukocytes, the cells were labelled with FITC anti-mouse CD45, PE anti-mouse IL-21, Percp-cy5.5 anti-mouse CD3, PE-cy7 anti-mouse CD4 and APC anti-mouse γδTCR. Stained cells were measured by FACS Calibur flow cytometry (BD Biosciences, San Jose, CA, USA), and data were analysed using CellQuest software (BD Biosciences) by a technician who was blinded to treatment groups. Caltag Counting Beads (Invitrogen Life Technologies, USA) were used to calculate the absolute number of cells.

Cell isolation and culture

Neonatal CMs were isolated from ventricles of 1-day-old C57BL/6 mice using previously described methods with some modifications (Rui *et al.*, 2001). Briefly, neonatal mice were killed by cervical dislocation, and their ventricles were minced and digested with Liberase TH (0.1 $U \cdot mL^{-1}$ in HBSS). After being filtered through a nylon cell strainer (70 μm size; BD Falcon, Franklin Lakes, NJ, USA), the collected cells were incubated in 5% CO_2 at 37°C for 1 h. CFs were separated from CMs via differential plating, during which CMs did not attach to the culture flasks. The cells were then separately cultured with high-glucose DMEM cell culture containing 10% FBS, 1% penicillin and streptomycin. CMs were used in experiments after they had formed a confluent monolayer and were contracting in synchrony at 72 h. CFs from passages 2 and 3 were used for the experiment.

Neutrophils were isolated from the marrow of the femurs and tibias of adult mice through density gradient centrifugation as previously described (Lowell *et al.*, 1996; Siemsen *et al.*, 2007). Briefly, after the mice had been killed by cervical dislocation, the long bones of the hind legs were removed, and the ends were clipped. The bone marrow cells were flushed from the tibias and femurs with HBSS and filtered through a cell strainer (40 μm size, BD Falcon). The suspension was subject to a Percoll (GE Healthcare, Sweden) step gradient. Cells were collected from the neutrophil-enriched fraction, followed by a further isolation with Histopaque 1119. Purity of neutrophils was evaluated by flow cytometry (Ly-6G/Gr-1 and CD11b double-positive cells >85%).

ELISA

Levels of KC and MIP-2 in the conditioned supernatant were quantified using commercial ELISA kits (R&D Systems, Minneapolis, MN, USA) according to the manufacturer's instructions. The absorbance of each well was determined at 450 nm using a microplate reader (Elx800, Bio-Tek, USA).

Neutrophil migration assays

Neutrophil migration was measured using transwell inserts with polycarbonate filter (5 μm pores, Corning, NY, USA) preloaded in 24-well tissue culture plates. Freshly isolated neutrophils (1×10^6 cells) were added to the upper chambers of the transwell inserts, and conditioned supernatants from CMs or CFs were added to the lower well. After 60 min of incubation, the number of migrated neutrophils in the lower chamber was counted in five randomly chosen fields using an

inverted microscope (Ruddy *et al.*, 2004). The analysis was carried out by an investigator who was blinded to the experimental groups.

Quantitative RT-PCR

Total RNA was extracted from ischaemic tissue or cells using Trizol (Invitrogen, Carlsbad, CA, USA) and reverse transcribed into cDNA using the PrimeScript RT reagent kit (Takara Biotechnology, Dalian, China) according to the manufacturer's instructions. The mRNA levels of the target genes were quantified using SYBR Green Master Mix (Takara Biotechnology, Dalian, China) with the CFX96 Real-Time PCR Detection System (Bio-Rad, Berkeley, CA, USA). Data from each sample were normalized to β-actin. The primer sequences are shown in Supporting Information Table S1.

Western blotting

Protein extracted from tissues or cells was separated on 10–12% SDS-PAGEs and transferred to PVDF membranes. After being blocked with 5% skimmed milk in Tris-buffered saline (TBS)(1×) for 2 h, the membranes were incubated with indicated primary antibodies at 4°C overnight, followed by incubation with HRP-conjugated secondary antibody for 2 h. The specific bands were detected using the Super ECL reagent (Pierce, Rockford, IL, USA). Images were obtained and analysed using Image Lab 3.0 software. The intensity of the GAPDH band was used as a loading control for comparison between samples.

Statistical analysis

The data and statistical analysis in the present study comply with the recommendations on experimental design and analysis in pharmacology (Curtis *et al.*, 2015). Data were collected and analysed in a blinded manner. Data are presented as the means ± SEM. For normally distributed data, differences were evaluated using Student's unpaired *t*-test between two groups. When comparing ≥3 different groups, one-way ANOVA followed by Tukey's *post hoc* test was used for multiple comparisons, and Dunnett's *post hoc* test was used when comparing each group with a control, only if F reached significance and there was no significant variance inhomogeneity. All analyses were performed using SPSS 13.0 (SPSS, Chicago, IL, USA), and statistical significance was set at $P < 0.05$ (two-tailed).

Materials

Anti-mouse IL-21 monoclonal antibody (clone: FFA21), isotype control antibody (clone: eBR2a), PE-cy7 anti-mouse CD11b, PE anti-mouse Ly-6G/Gr-1, FITC anti-mouse CD45, PE anti-mouse IL-21, Percp-cy5.5 anti-mouse CD3, PE-cy7 anti-mouse CD4 and APC anti-mouse γδTCR were obtained from eBioscience (San Diego, CA, USA). Recombinant mouse-IL-21 and primary antibodies to mouse IL-21 and IL-21 receptor were purchased from R&D Systems (Minneapolis, MN, USA). Anti-mouse anti-Ly6G monoclonal antibody (clone: 1A8) and isotype control antibody (clone: RTK2758) were obtained from Biolegend (San Diego, CA, USA). Recombinant murine TNF-α was purchased from PeproTech Inc. (Rocky Hill, NJ, USA). Evans blue, TTC, hydrogen peroxide (H_2O_2) solution, BSA and Histopaque-1119 were purchased from Sigma-Aldrich (St. Louis, MO, USA). **LY294002** and antibodies to phospho-Akt (Ser^{473}), phospho-p38 (Thr^{180}/Tyr^{182}), phospho-ERK (Thr^{202}/Tyr^{204}), phospho-NF-κ-B p65 (Ser^{536}), phospho-Stat1 (Tyr^{701}), phospho-Stat3 (Tyr^{705}), Akt, p38 MAPK, ERK, NF-κ-B p65, Stat1 and Stat3 were purchased from Cell Signalling Technology (Danvers, MA, USA). Antibody against GAPDH was purchased from AntGene (Wuhan, China). **BAY11-7082** and **SB203580** were obtained from Selleckchem (Houston, TX, USA). Collagenase B and Liberase TH were obtained from Roche Diagnostics GmbH (Mannheim, Germany). High-glucose DMEM, HBSS and FBS were purchased from GIBCO (Carlsbad, CA, USA).

Nomenclature of targets and ligands

Key protein targets and ligands in this article are hyperlinked to corresponding entries in http://www.guidetopharmacology.org, the common portal for data from the IUPHAR/BPS Guide to PHARMACOLOGY (Southan *et al.*, 2016), and are permanently archived in the Concise Guide to PHARMACOLOGY 2015/16 (Alexander *et al.*, 2015a,b).

Results

Increased expression of IL-21 and its receptor in the myocardium post-reperfusion

We first examined the expression kinetics of IL-21 in the ischaemic myocardium via quantitative real-time PCR. As illustrated in Figure 1A, mRNA expression of IL-21 increased rapidly within 30 min after reperfusion, peaked at 6 h and remained elevated but with a declining trend for up to 24 h. Likewise, protein expression of IL-21 was up-regulated as early as 30 min after reperfusion, reaching peak expression at 24 h (Figure 1B). Multiple cell types, including T-cells and innate immune cells, can produce IL-21 (Sutton *et al.*, 2009; Clarkson *et al.*, 2014). To determine which leukocytes account for the increase in IL-21 in the ischaemic myocardium, we used intracellular cytokine staining combined with staining for some surface markers. Over 80% of the IL-21-secreting leukocytes were $CD3^+$ T-cells, including about 77% $CD4^+$ cells and 1% $\gamma\delta TCR^+$ cells, indicating that $CD4^+$ cells were the major source of IL-21 (Figure 1E).

IL-21 exerts biological effects through binding to its receptor, a heterodimer of the IL-21 receptor and the common cytokine receptor γ_c. In the present study, we found that both mRNA and protein expression levels of the IL-21 receptor were increased at 12 h and that they remained elevated until 24 h (Figure 1C, D). Furthermore, in our *in vitro* study, we found that IL-21 receptor gene expression in neonatal mouse CMs was increased at 1 h and reached a peak at 8 h after the induction of oxidative stress with H_2O_2. Meanwhile, the mRNA expression of IL-21 receptors in CFs was increased at 4 h and reached a peak at 12 h after being treated with TNF-α (Supporting Information Figure S1).

Neutralization of endogenous IL-21 attenuates myocardial injury, whereas exogenous IL-21 aggravates it

The early up-regulation of IL-21 and its specific receptor, IL-21 receptor, in post-ischaemic myocardium indicates a

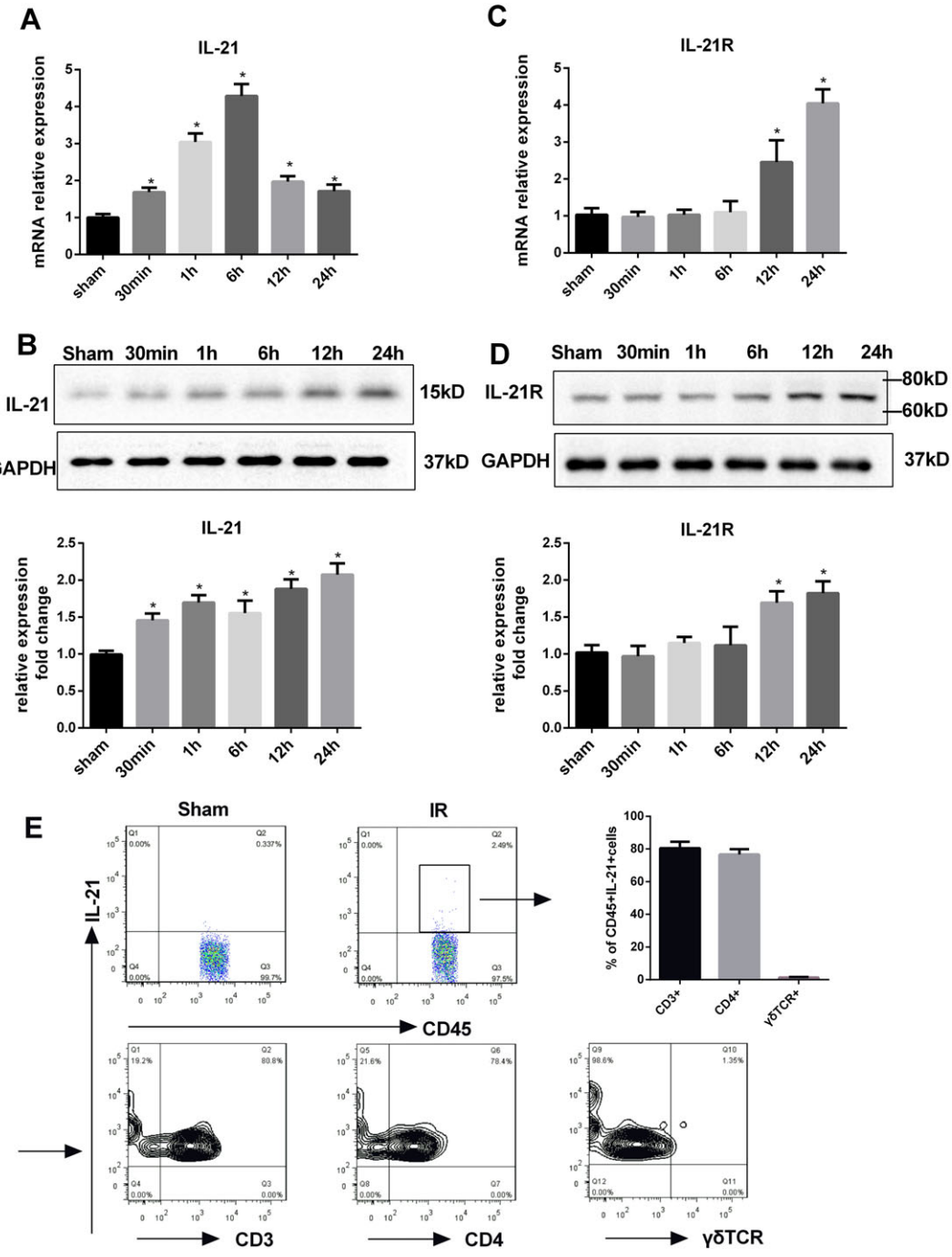

Figure 1

IL-21 and IL-21 receptors are elevated during the acute phase of MIRI and CD4$^+$ T-cells are the major source of IL-21 in the ischaemic myocardium. The time course of changes in the (A) mRNA and (B) protein expression of IL-21 in the myocardium following MIRI were measured by quantitative real-time PCR and western blotting, respectively ($n = 6$ per group). The time course of changes in the (C) mRNA and (D) protein expression of IL-21 receptors (IL-21R) in the myocardium following MIRI were measured via quantitative real-time PCR and western blotting, respectively ($n = 6$ per group). (E) The infiltrated IL-21$^+$ leukocytes in myocardial I/R mice after 6 h of reperfusion were analysed by flow cytometry. CD45$^+$ cells were isolated and restimulated. The IL-21$^+$ CD45$^+$ cells were further analysed for CD3, CD4 and γδTCR expression to detect the cellular source of IL-21. The proportion of different IL-21-secreting cells in the IL-21$^+$CD45$^+$ cells were quantitatively analysed ($n = 5$ per group). *$P < 0.05$ versus sham.

potential role of IL-21 in MIRI. Therefore, we examined the functional significance of IL-21 in MIRI by treating mice with an anti-IL-21 neutralizing antibody or recombinant IL-21 before reperfusion. In comparison with the effects observed in isotype-treated mice, anti-IL-21 neutralizing antibody administration reduced infarct size (Figure 2B), decreased cTnT levels (Figure 2C) and restored cardiac function as shown by improving LV EF and FS (Figure E). In contrast,

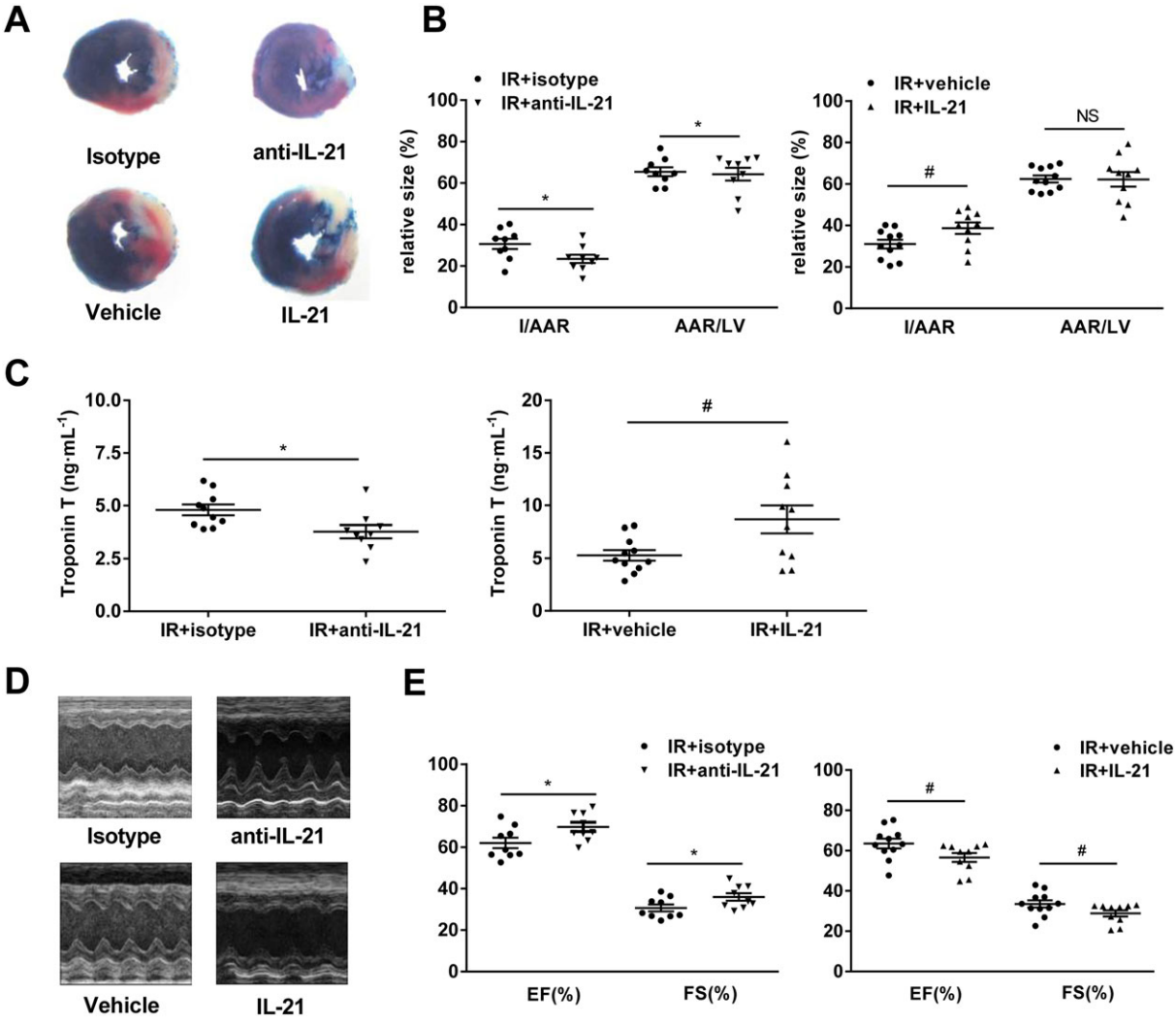

Figure 2

IL-21 neutralization attenuates, whereas exogenous IL-21 aggravates, myocardial injury. (A) Representative images of left ventricular slices from different groups 1 day after reperfusion. The non-ischaemic area is indicated in blue, the area at risk (AAR) in red and the infarct area (I) in white. (B) Quantification of infarct size of myocardial tissues 1 day after reperfusion. (C) Serum cTnT was measured 1 day after reperfusion. (D) Representative M-mode echocardiographic images of the left ventricular 1 day after reperfusion. (E) Left ventricular EF and FS were measured via echocardiography 1 day after reperfusion. *$P < 0.05$ versus isotype; $^{\#}P < 0.05$ versus vehicle. Isotype, $n = 9$; anti-IL-21, $n = 9$; vehicle, $n = 11$; IL-21, $n = 10$.

exogenous IL-21 administration significantly increased infarct size, elevated cTnT levels and reduced cardiac function in comparison with the effects observed in vehicle-treated mice (Figure 2). Collectively, these findings indicated that IL-21 played a pathogenic role in MIRI.

IL-21 mediates neutrophil recruitment through the regulation of CXC chemokines in vivo

Infiltrated inflammatory cells play key roles in prolonging myocardial ischaemic injury. Of these cells, neutrophils are the predominant type that accumulates in the reperfused myocardium within the first hours after reperfusion (Dreyer *et al.*, 1991; Yan *et al.*, 2013). To determine whether IL-21 is involved in neutrophil recruitment in the context of MIRI, we analysed the absolute counts and frequency of $CD11b^{+}Gr\text{-}1^{+}$ neutrophils infiltrating the ischaemic myocardium 3 h after reperfusion via flow cytometry. In comparison with infiltration in sham-operated mice, there was an obvious increase in neutrophil infiltration in the reperfused myocardium (I/R-mice). Moreover, exogenous IL-21 administration further increased neutrophil infiltration (Figure 3A, B), while anti-IL-21 neutralizing antibody treatment reduced neutrophil infiltration (Figure 3C, D). To examine whether neutrophils are directly related to the myocardial ischaemic injury after exogenous IL-21 administration, we conducted a neutrophil depletion study. After depletion of neutrophils by anti-Ly6G antibody, the number of neutrophils infiltrating the ischaemic myocardium markedly declined (Supporting Information Figure S2A). Furthermore, depletion of neutrophils in mice treated with exogenous IL-21 decreased

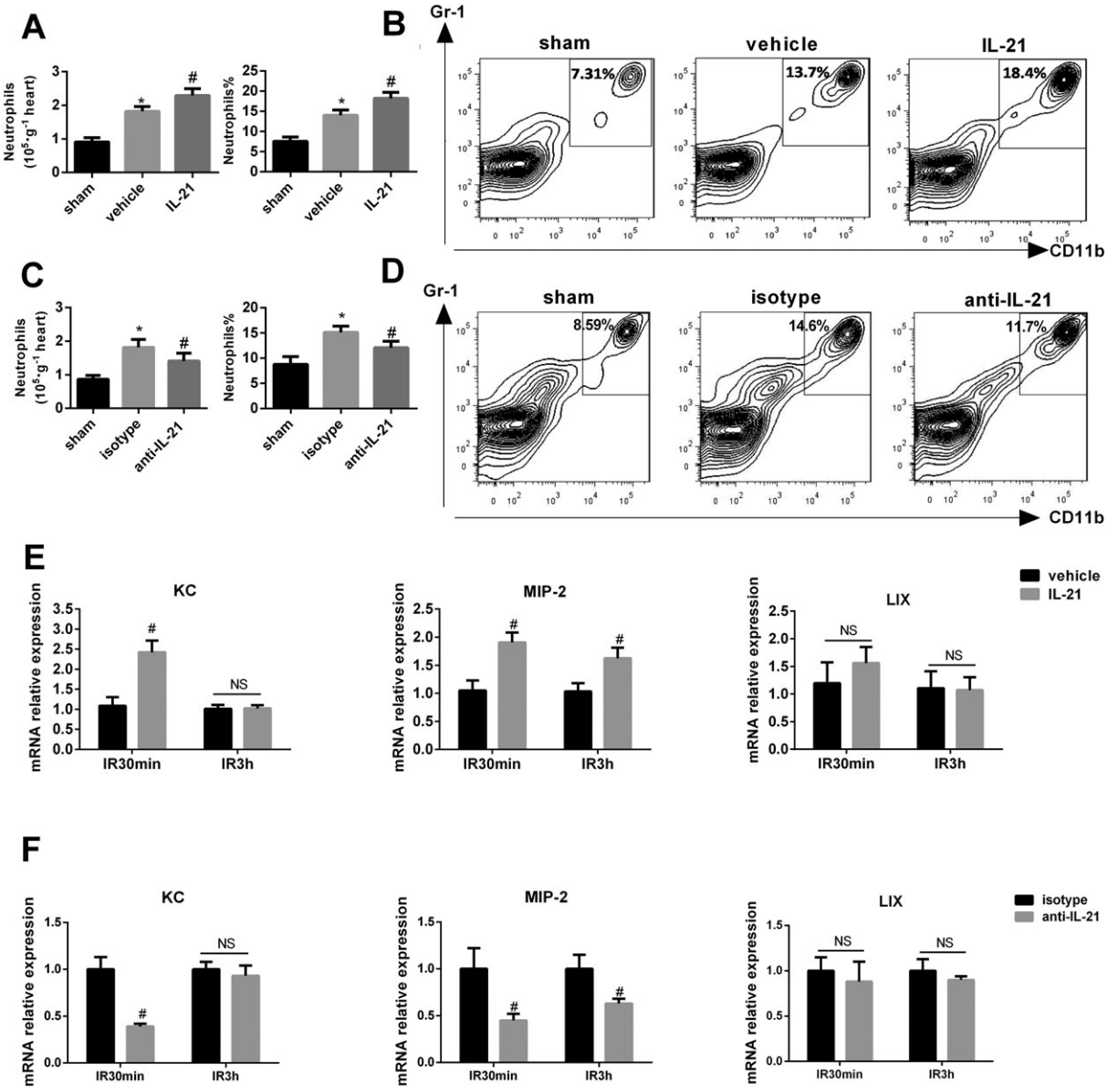

Figure 3

IL-21 increases the number of neutrophils infiltrating the myocardium and the myocardial expression of KC and MIP-2 following MIRI, while anti-IL-21 mAb reduced cardiac infiltration of neutrophils and the expression of KC and MIP-2. (A–D) The number, percentage and representative contour plots of $CD11b^{+}Gr\text{-}1^{+}$ neutrophils infiltrating the myocardium after 30 min of ischaemia and 3 h of reperfusion were analysed by flow cytometry (n = 5 per group). (E, F) The mRNA expression of KC, MIP-2 and LIX in the myocardium after 30 min of ischaemia followed by 30 min or 3 h of reperfusion was analysed via real-time PCR (n = 5 per group). *$P < 0.05$ versus Sham; #$P < 0.05$ versus vehicle or isotype.

infarct size, reduced cTnT levels and improved cardiac function compared with isotype antibody group (Supporting Information Figure S2B–D). These results indicated that neutrophils were essential for IL-21-induced myocardial ischaemic injury.

ELR-containing CXC chemokines KC, MIP-2 and LPS-induced CXC chemokine (LIX) are reported to be potent neutrophil chemoattractants (Frangogiannis and Entman, 2005). Therefore, we further investigated the potential effects of IL-21 on the myocardial expression of these chemokines via real-time PCR. Relative to the effects in vehicle-treated mice, IL-21 administration rapidly up-regulated KC and MIP-2 mRNA expression as early as 30 min after reperfusion. This elevation persisted for 3 h for MIP-2. However, no significant changes were observed in the expression of LIX (Figure 3E). In addition, the mRNA expression of KC and MIP-2 was reduced in the ischaemic myocardium after neutralization of endogenous IL-21 (Figure 3F).

IL-21 promotes neutrophil migration and the expression of KC and MIP-2 in CMs and CFs

To determine the direct effects of IL-21 on different cell types involved in this process, we isolated neutrophils from adult

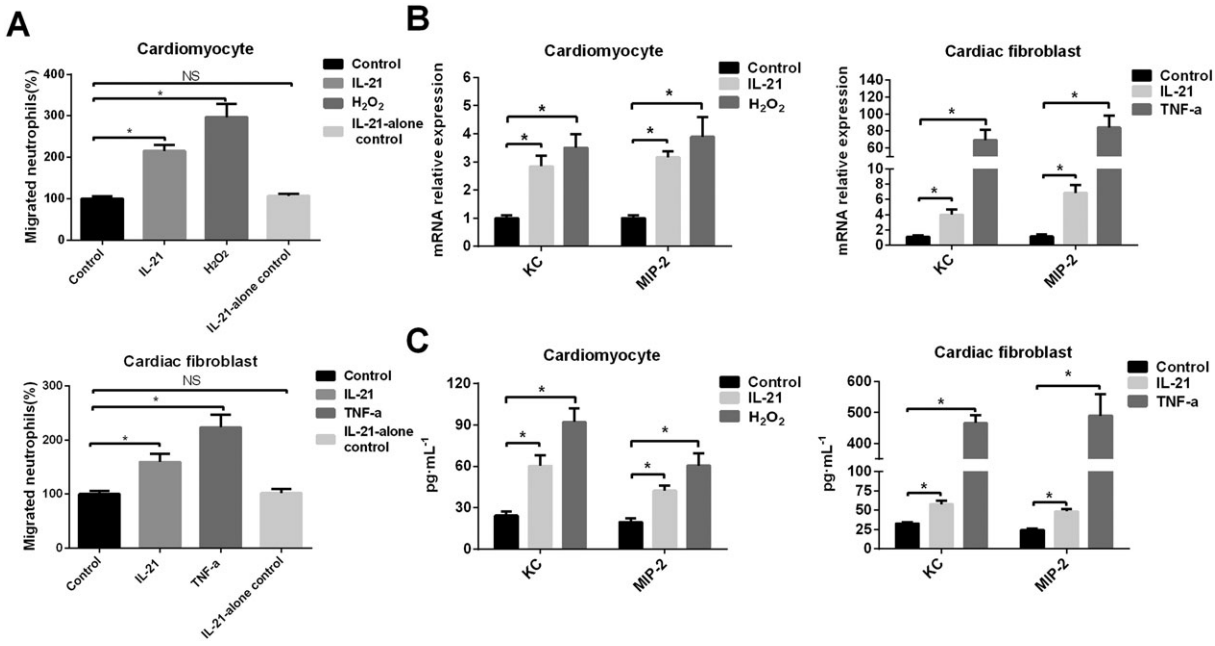

Figure 4

IL-21 induces neutrophil migration and the expression of KC and MIP-2 in CMs and CFs. (A) Neutrophil migration in the presence of conditioned supernatants from stimulated CMs (upper) and CFs (lower) was measured by transwell assay. The values were normalized relative to those of the medium from unstimulated CMs or CFs (control). (B) The mRNA expression of KC and MIP-2 in response to 1 h of stimulation with IL-21 (100 ng·mL^{-1}) in CMs (left) and CFs (right). (C) ELISA results for KC and MIP-2 levels in the supernatants of CMs (left) and CFs (right) stimulated by IL-21(100 ng·mL^{-1}) for 24 h. H_2O_2 (100 μM) or TNF-α (5 ng·mL^{-1}) served as positive controls for CMs and CFs respectively. IL-21-alone control media was from unstimulated cells 'spiked' with IL-21. Data are representative of five independent experiments. *$P < 0.05$ versus control.

mouse bone marrow and prepared CM/CF primary cultures from neonatal mice. Neutrophil migration assays indicated an enhanced neutrophil migration in the presence of conditioned medium from CMs or CFs treated with IL-21, relative to the effects observed in the presence of conditioned medium from unstimulated cells (Figure 4A). We then examined the effects of IL-21 on the expression of KC/MIP-2 in CMs and CFs. As shown in Figure 4B, IL-21 up-regulated KC and MIP-2 mRNA expression in CMs and CFs. Moreover, as detected via ELISA, IL-21 also increased KC and MIP-2 secretion by both CMs and CFs (Figure 4C).

Signalling mechanisms underlying the effects of IL-21

IL-21-mediated cellular effects have been reported to be associated with the ERK, p38 MAPK, PI3K/Akt, NF-κB and signal transducers and activators of transcription (STAT)1/3 signalling pathways (Pelletier *et al.*, 2004; Caruso *et al.*, 2007a,b; de Totero *et al.*, 2008; Xing *et al.*, 2016), which are also involved in MIRI (Lopez-Neblina and Toledo-Pereyra, 2006). To further elucidate the mechanisms by which IL-21 affects MIRI, we focused on these signalling pathways. We first explored the time course of the changes in these signalling pathways in the myocardium. We found that reperfusion increased the phosphorylation of ERK, p38 MAPK and NF-κB p65 as early as 10 min, while the activation of Akt, STAT1 and STAT3 occurred at 30 min after reperfusion (Supporting Information Figure S3). We further examined the effects of IL-21 on each signalling pathway at both 10 and 30 min after reperfusion. As shown in Figure 5, IL-21 further increased the phosphorylation of p38 MAPK at both 10 and 30 min after reperfusion and enhanced NF-κB p65 activation at 30 min after reperfusion.

To examine the direct effects of IL-21 on isolated CMs/CFs, we assessed the activation kinetics of the above-mentioned signalling pathways at a cellular level. As demonstrated in Figure 6, CMs and CFs responded to IL-21 with different signalling kinetics, suggesting a cell-type-specific response. In CMs, the phosphorylation of Akt was enhanced by IL-21 administration at early time points (10–30 min), and it then returned to baseline at 1 h. NF-κB p65 phosphorylation was induced within 30 min of IL-21 administration and remained elevated for up to 2 h. Stimulation with IL-21 in CFs induced the activation of p38 MAPK signalling within 30 min, which remained elevated for 2 h. NF-κB p65 phosphorylation was induced at 1 h and was maintained for up to 2 h. However, the activity of Akt in IL-21-treated CFs exhibited an opposite trend in comparison to that observed in CMs, showing a slightly inhibited activity at 30–60 min after IL-21 administration. There were no significant changes in the activity of the ERK, STAT1 or STAT3 signalling pathways following stimulation with IL-21 in either CMs or CFs (data not shown).

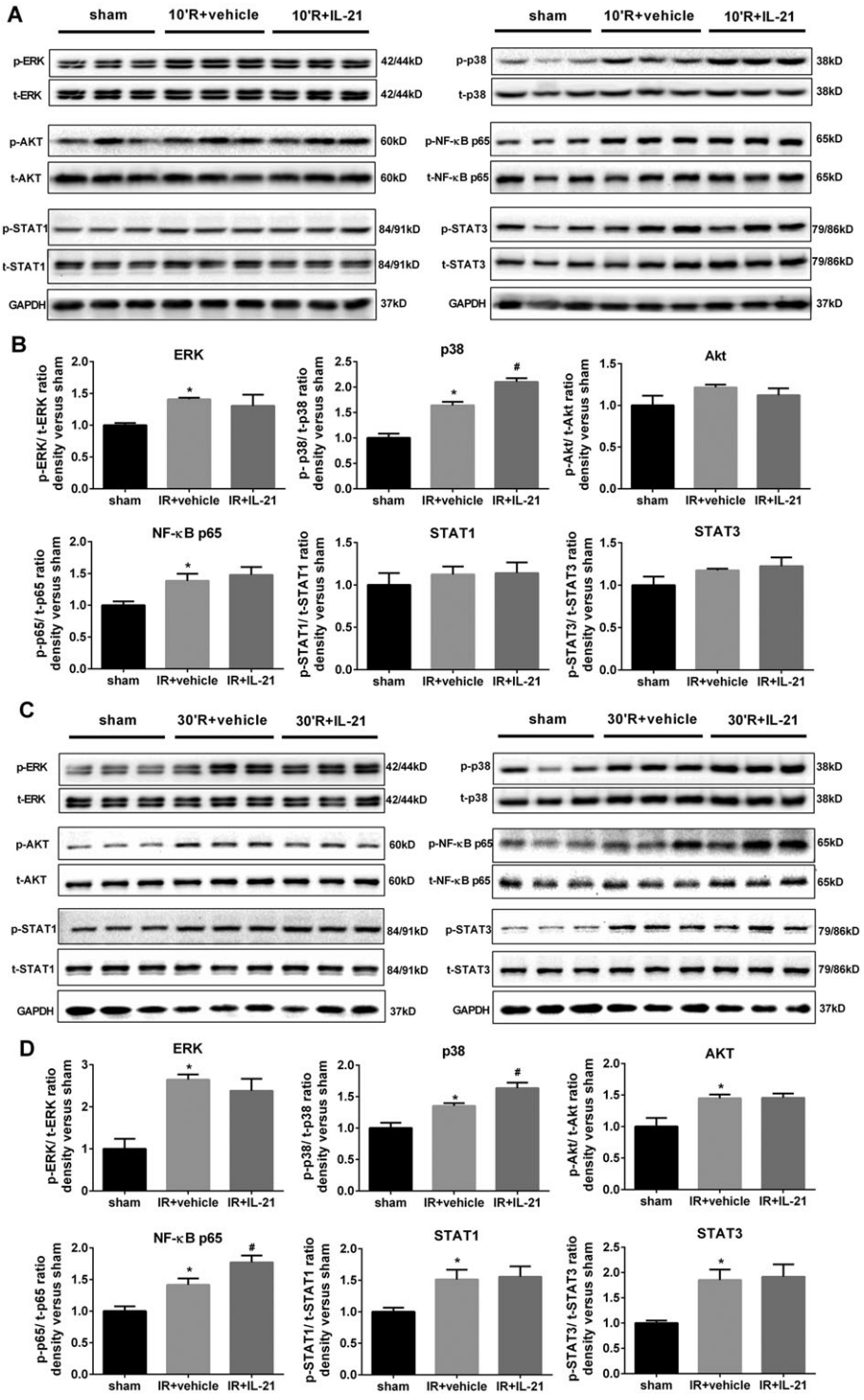

Figure 5

Activation of the ERK, p38 MAPK, Akt, NF-κB, STAT1 and STAT3 signalling pathways in the myocardium after the administration of exogenous IL-21. (A) Representative western blots showing the activation of different signalling pathways 10 min after reperfusion in the myocardium after IL-21 administration. (B) Quantitative analysis of the levels of phospho-/total-ERK, p38 MAPK, Akt, NF-κB, STAT1 and STAT3 signalling pathways 10 min after reperfusion in different groups ($n = 6$ per group). (C) Representative western blots showing the activation of different signalling pathways 30 min after reperfusion in the myocardium after IL-21 administration. (D) Quantitative analysis of the levels of phospho-/total-ERK, p38 MAPK, Akt, NF-κB, STAT1 and STAT3 signalling pathways 30 min after reperfusion in different groups ($n = 6$ per group). *$P < 0.05$ versus sham; $^{\#}P < 0.05$ versus vehicle.

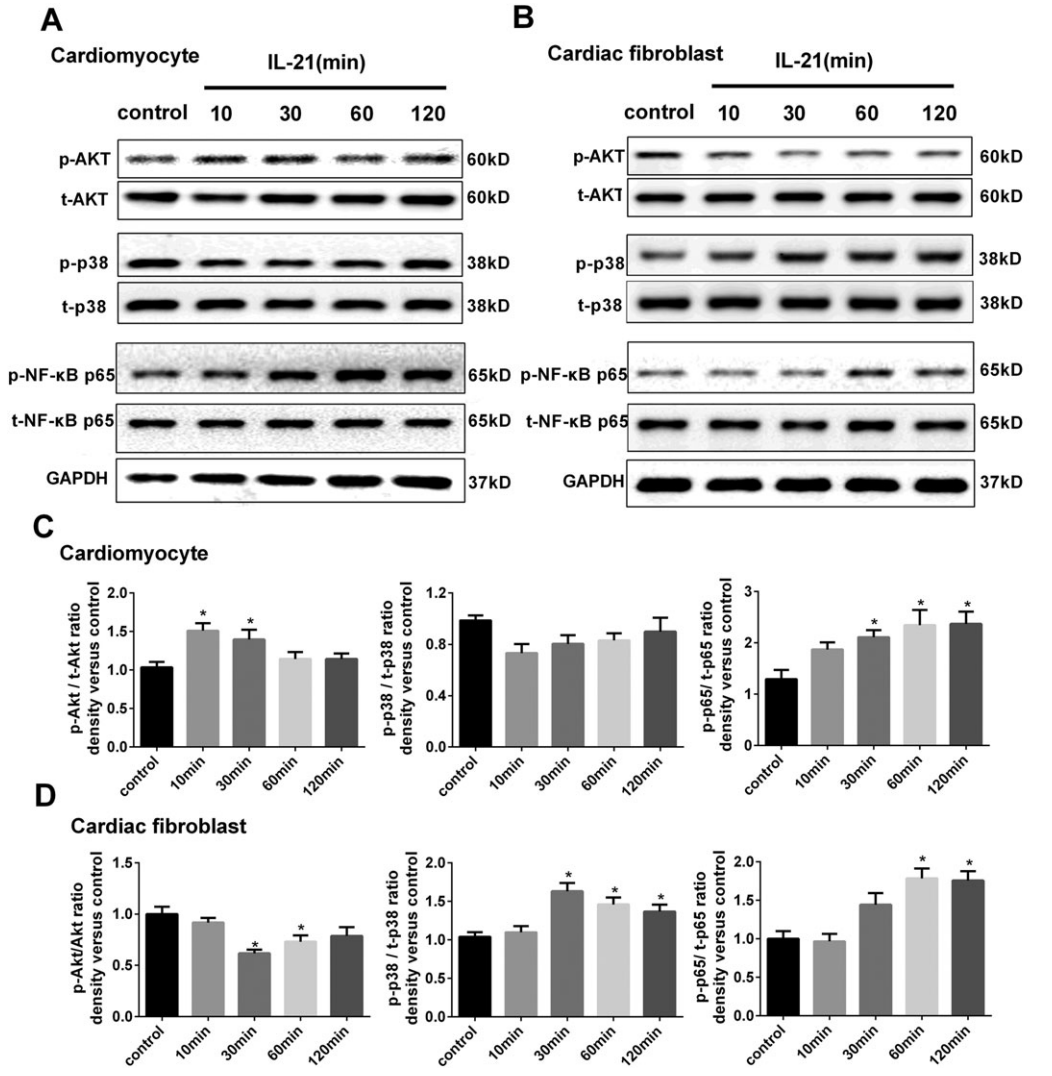

Figure 6

Direct effects of IL-21 on the activation of Akt, p38 MAPK and NF-κB signalling in isolated CMs and CFs. (A, B) Representative western blots showing the phospho-/total-Akt, p38 MAPK and NF-κB p65 levels in CMs and CFs unstimulated (control) or stimulated with IL-21 (100 ng·mL^{-1}) for indicated durations. (C, D) Quantitative analysis of the phospho-/total-Akt, p38 MAPK and NF-κB p65 levels in CMs and CFs. Data are representative of five independent experiments. *$P < 0.05$ versus control.

IL-21 induces KC and MIP-2 expression through Akt/NF-κB or p38 MAPK/NF-κB signalling

Next, we examined whether the IL-21-dependent up-regulation of CXC chemokines is associated with IL-21-mediated activation of Akt, p38 MAPK and NF-κB signalling. CMs were pre-incubated with an Akt inhibitor (LY294002 10 μM) or NF-κB inhibitor (BAY11–7082 10 μM), while CFs were pre-incubated with a p38 MAPK inhibitor (SB203580 10 μM) or BAY11–7082. IL-21 was then added to the culture media, and the mRNA and protein expressions of KC and MIP-2 were assessed via real-time PCR and ELISA. The short-term incubation with the inhibitors had no effect on the basal levels of chemokine expressions in both CMs and CFs. Pre-incubation with either the Akt or NF-κB inhibitor abolished the IL-21-induced increase in KC and MIP-2 mRNA expression in CMs, whereas KC and MIP-2 secretions in the presence of IL-21 were partially inhibited by either LY294002 or BAY11-7082 (Figure 7A, B). In CFs, the inhibition of either p38 MAPK or NF-κB significantly reduced the IL-21-mediated up-regulation of KC and MIP-2 mRNA expression. Likewise, the IL-21-induced KC and MIP-2 secretions were partially inhibited by either SB203580 or BAY11-7082 (Figure 7C, D).

Our previous time course study indicated that the IL-21-induced phosphorylation of Akt and p38 MAPK preceded the phosphorylation of NF-κB in CMs and CFs respectively. Therefore, we further assessed whether Akt and p38 MAPK act as upstream regulators. We found that a pre-incubation with Akt or p38 MAPK inhibitors partially reduced IL-21-induced activation of NF-κB signalling in CMs or CFs, respectively, suggesting that NF-κB activation may occur, at

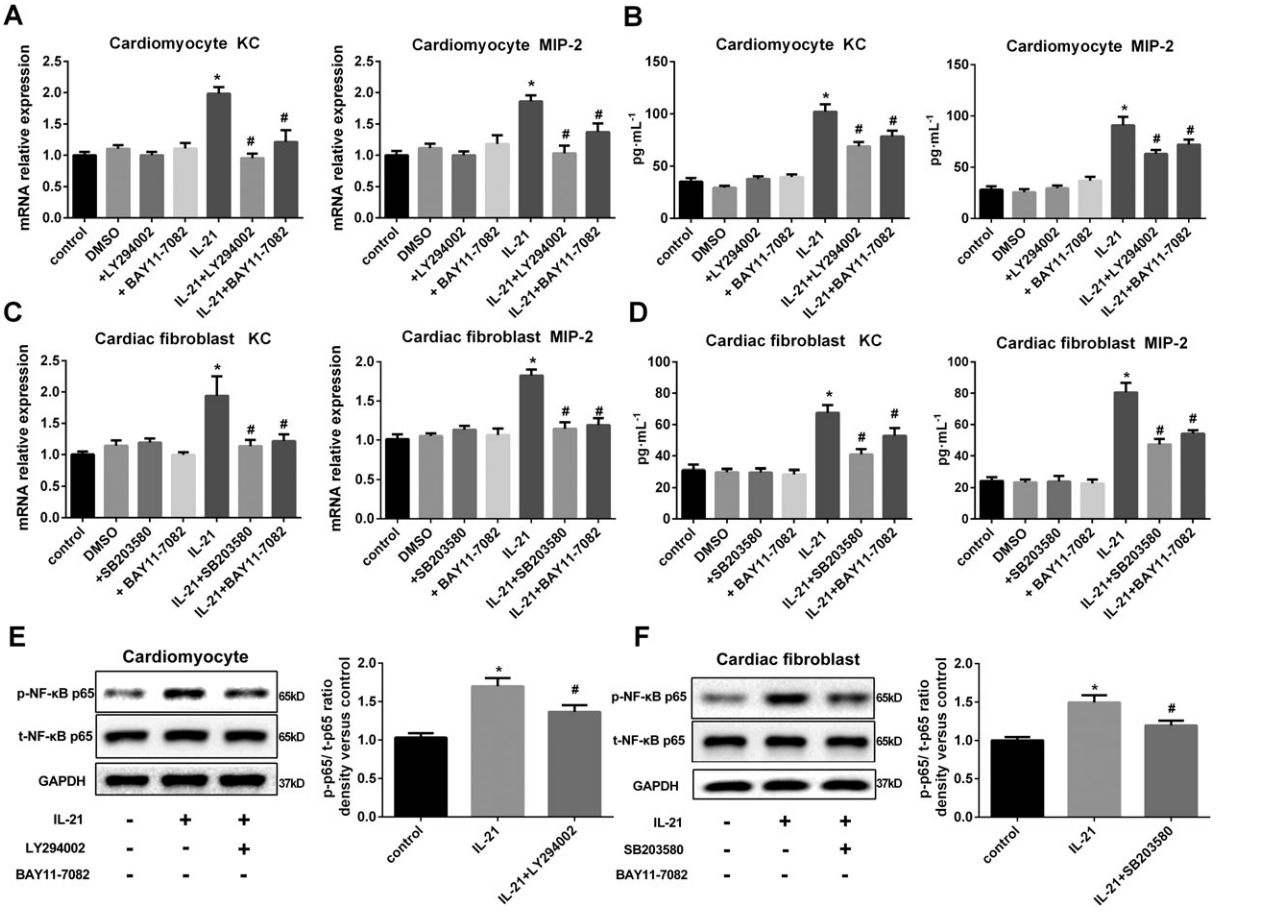

Figure 7

IL-21-induced chemokine expression is Akt/NF-κB or p38 MAPK/NF-κB dependent. (A) CMs were pretreated for 1 h with an Akt inhibitor (LY294002, 10 μM) or an NF-κB inhibitor (BAY11-7082, 10 μM), followed by IL-21 (100 ng·mL^{-1}) stimulation for 1 h. The expression of KC and MIP-2 was measured via real-time PCR. (B) CMs were pretreated for 1 h with the indicated inhibitors, followed by IL-21 stimulation for 24 h. Concentrations of KC and MIP-2 in the culture media were measured by ELISA. (C) CFs were pretreated for 1 h with a p38 MAPK inhibitor (SB203580, 10 μM) or an NF-κB inhibitor (BAY11-7082, 10 μM), followed by IL-21 (100 ng·mL^{-1}) stimulation for 1 h. The expression of KC and MIP-2 was measured by real-time PCR. (D) CFs were pretreated for 1 h with the indicated inhibitors, followed by IL-21 stimulation for 24 h. Concentrations of KC and MIP-2 in the culture media were measured by ELISA. (E) CMs were pretreated with LY294002, and (F) CFs were pretreated with SB203580 and then cells were stimulated with IL-21 or vehicle for 1 h. NF-κB p65 phosphorylation was analysed by western blotting. Representative western blot images (left) and quantitative analyses (right) are shown. Data are representative of five independent experiments. *$P < 0.05$ versus control; $^{\#}P < 0.05$ versus IL-21.

least in part, downstream of Akt and p38 MAPK signalling following IL-21 exposure (Figure 7E, F).

Discussion and conclusions

The current study demonstrates a key role for IL-21 in myocardial injury in MIRI mice models. The data revealed that IL-21 was elevated during the acute phase of MIRI, and CD4^{+}T-cells may be a major source of IL-21 production. Treatment with exogenous IL-21 markedly exacerbated the myocardial injury, which was related to an increase in KC and MIP-2 expression and infiltration of neutrophils. Treatment with the anti-IL-21 mAb induced the opposite effect. *In vitro* studies revealed that IL-21 could induce KC and MIP-2 expression, mainly through Akt/NF-κB signalling in CMs and p38 MAPK/NF-κB signalling in CFs. Furthermore, the neutrophil depletion study confirmed that IL-21 aggravated myocardial injury mainly by increasing neutrophil infiltration.

There is emerging evidence suggesting that IL-21 mediates multiple types of tissue damage and is an exacerbating factor in the pathogenesis of several inflammatory diseases, including inflammatory bowel disease, experimental autoimmune encephalomyelitis, rheumatoid arthritis, psoriasis and type I diabetes (Monteleone *et al.*, 2009; Di Fusco *et al.*, 2014; Gharibi *et al.*, 2016). Moreover, IL-21 has also been explored as a biomarker associated with the development of coronary artery disease (Ding *et al.*, 2014) and LV remodelling after AMI (Weir *et al.*, 2012). However, the pathological role of IL-21 in the acute inflammatory response, especially during ischaemia/reperfusion injury, remains largely unknown.

In a mouse model of MIRI, we observed an early up-regulation of IL-21 and its functional receptor in the

myocardium, supporting the hypothesis that IL-21 acts in the early stages of MIRI. Several immune cells have been reported to produce IL-21, including $CD4^+$ T-cells, γδT-cells, neutrophils and NK-cells (Coquet *et al.*, 2007; Sutton *et al.*, 2009; Puga *et al.*, 2012; Clarkson *et al.*, 2014). Our study revealed that $CD4^+$ T-cells mainly account for the production of IL-21 during MIRI. We further demonstrated that neutralization of endogenous IL-21 attenuated myocardial injury; conversely, exogenous IL-21 administration increased infarct size and reduced cardiac function. This observation is consistent with previous studies showing that IL-21 plays a pathogenic role in tissue I/R injury. Feng *et al.* have reported an increase in IL-21 production at the initial stage of mouse liver IRI, which led to IL-17A production by NK cells, and promoted liver injury (Feng *et al.*, 2012). More recently, IL-21 was found to be robustly up-regulated in mice within 24 h after cerebral reperfusion injury and to contribute to both immediate and delayed brain injury (Clarkson *et al.*, 2014).

Neutrophils are the most abundant leukocyte subset present during the first hours after ischaemia reperfusion in the myocardium (Dreyer *et al.*, 1991; Yan *et al.*, 2013), and their infiltration is considered to be a critical event in MIRI, serving as the major source of reactive oxygen species and proteolytic enzymes (Vinten-Johansen, 2004). Previous evidence suggested that IL-21 may be involved in neutrophil recruitment and activation. IL-21 has been shown to indirectly induce the accumulation of neutrophils in a murine air-pouch model (Pelletier *et al.*, 2004) and enhance lung infiltration by neutrophils through up-regulation of KC expression (Spolski *et al.*, 2012). Recent research by Takeda *et al.* indicates that IL-21 up-regulates the surface expression of CD11b and CD16 and enhances the phagocytic ability and ROS production of human peripheral blood neutrophils (Takeda *et al.*, 2014). Despite the above-mentioned findings, whether IL-21 affects neutrophil recruitment in relation to tissue ischaemic reperfusion injury had not yet been examined. Our *in vivo* study shows that IL-21 can induce myocardial neutrophil infiltration during the early stage of reperfusion through the induction of KC and MIP-2 expression. Whereas, neutralization of endogenous IL-21 reduced the accumulation of neutrophils and expression of KC and MIP-2 in myocardial tissue. Our *in vitro* study further confirmed that IL-21 has direct effects on CMs and CFs, increasing KC and MIP-2 expression at both the mRNA and protein levels and enhancing the migratory ability of neutrophils.

In subsequent experiments, we investigated the signalling mechanisms underlying the IL-21-mediated effects. IL-21 has been previously reported to activate several

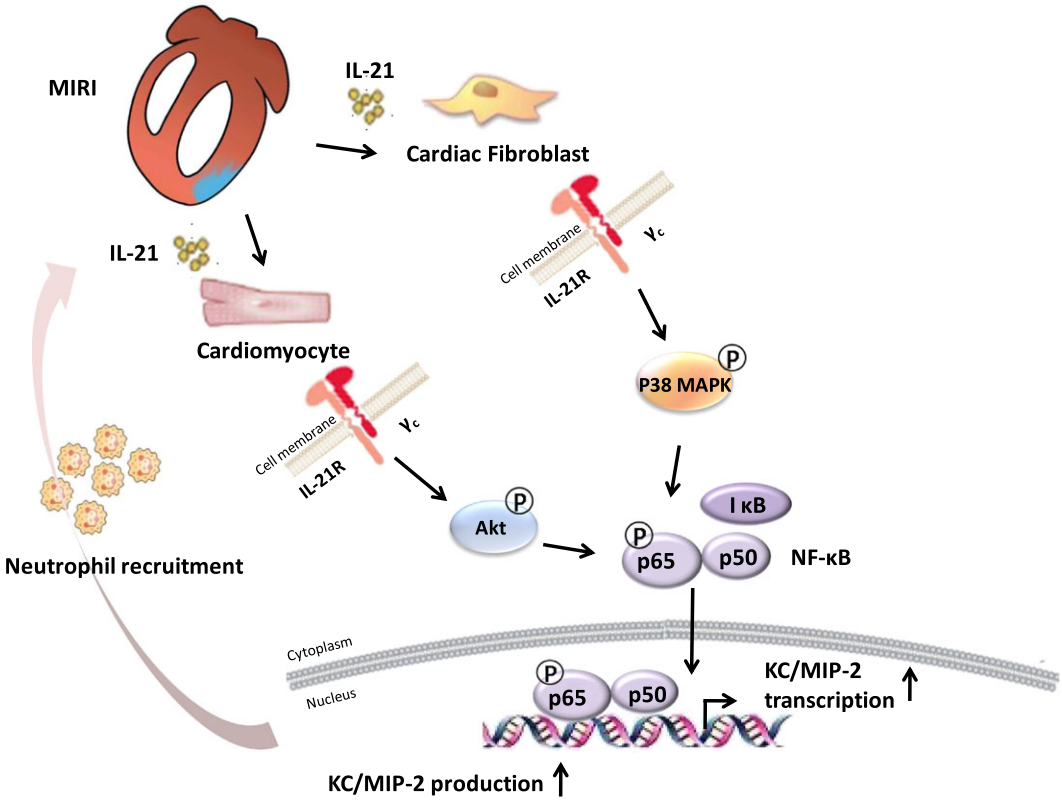

Figure 8

Schematic illustration of the IL-21-mediated effects on neutrophil recruitment in MIRI. MIRI induces the up-regulation of IL-21 in the myocardium, which directly acts on CMs and CFs to promote the mRNA expression and production of KC and MIP-2 via the activation of Akt/NF-κB and p38 MAPK/NF-κB signalling in CMs and CFs respectively. KC and MIP-2 are potent neutrophil chemoattractants, which recruit neutrophils into the injured myocardium.

signalling pathways, including JAK-STAT (primarily STAT1 and STAT3), ERK, p38 MAPK, PI3K/Akt and NF-κB in different tissues and cell types (Brenne *et al.*, 2002; Pelletier *et al.*, 2004; Caruso *et al.*, 2007a,b; Caruso *et al.*, 2009; Wang *et al.*, 2015; Xing *et al.*, 2016). Moreover, these signalling pathways are also known to be involved in the processes associated with MIRI (Lopez-Neblina and Toledo-Pereyra, 2006). Our *in vivo* study indicated that IL-21 activates p38 MAPK and NF-κB signalling, which are both important in the production of various pro-inflammatory mediators, including cytokines, chemokines and adhesion molecules (Van der Heiden *et al.*, 2010). At a cellular level, IL-21 induced Akt and, subsequently, NF-κB p65 activation in CMs, while in CFs, IL-21 induced the phosphorylation of p38 MAPK, which preceded the activation of NF-κB p65. Because Akt signalling was slightly inhibited in CFs after IL-21 stimulation, the opposite effects of IL-21 on CMs and CFs may explain why the activation of Akt was not observed in the ischaemic myocardium *in vivo*.

NF-κB has been characterized as a critical transcription factor that regulates most chemokines at the level of transcription, and several signalling pathways are reported to regulate the upstream NF-κB, including p38MAPK and PI3K/Akt. Previous reports indicated that an up-regulation of CXC chemokines could be induced by NF-κB activation via the PI3K/Akt/IKK pathway in various cell types (Lee *et al.*, 2012; Li *et al.*, 2003; 2015; Lin *et al.*, 2011). In the present study, the involvement of Akt/NF-κB and p38 MAPK/NF-κB signalling in IL-21-mediated chemokine expression was further confirmed by using the relevant signalling inhibitors, and the results of this inhibition were consistent with previous evidence indicating that CXC chemokine expression is induced via the activation of p38 MAPK, PI3K/Akt and NF-κB signalling in different cellular contexts (Lafontant *et al.*, 2006; Stephanou, 2002; Turner *et al.*, 2011). However, it should be noted that although the inhibition of Akt and NF-κB signalling could substantially suppress IL-21-induced KC/MIP-2 mRNA expression, it only reduced but did not prevent IL-21-induced secretion of KC/MIP-2 in CMs. Likewise, the inhibition of p38 MAPK and NF-κB signalling also partially inhibited the IL-21-induced secretion of KC/MIP-2 in CFs. These observations suggest that additional signalling pathways may be involved in the post-transcriptional regulation of these chemokines.

In conclusion, our study presents novel evidence for a pathogenic role of IL-21 in MIRI, most likely produced by promoting cardiac neutrophil infiltration and chemokine expression. A proposed scheme of the effects of IL-21 on MIRI is provided in Figure 8. Thus, IL-21 could be a promising molecular target for ameliorating reperfusion injury.

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Author contributions

K.-J.W., S.W., J.J., T.T. and N.X. designed the experiments; K.-J.W., S.W., J.J., X.Z., M.Z., B.-J.L., Y.-Z.L., X.-D.Z., J.-Y.L. and S.-F.N. conducted the experiments and performed data analysis; Y.-H.L., Q.W., X.T., Z.M., N.X. and X.C. reviewed and made important suggestions to the manuscript; N.X. and X.C. developed the concept and provided guidance during the study.

Conflict of interest

The authors declare no conflicts of interest.

Declaration of transparency and scientific rigour

This Declaration acknowledges that this paper adheres to the principles for transparent reporting and scientific rigour of preclinical research recommended by funding agencies, publishers and other organisations engaged with supporting research.

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article.

https://doi.org/10.1111/bph.13781

Table S1 Primer sequences in qRT-PCR.

Figure S1 H_2O_2 induces IL-21R gene expression in CMs and TNF-α induces IL-21R gene expression in CFs. Serum-starved CMs were treated with H_2O_2 (100 μM) and CFs were treated with TNF-α (5 ng·mL^{-1}) for different periods of time. The time course of changes in the mRNA expression of IL-21R was measured via quantitative real-time PCR. Data are shown as the means ± SEM of five individual experiments. * $P < 0.05$ versus control.

Figure S2 Depletion of neutrophils ameliorated the IL-21-induced myocardial ischaemic injury. (A) The number of CD11b$^+$Gr-1$^+$ neutrophils infiltrating the myocardium after 30 min of ischaemia and 3 h of reperfusion was analysed via flow cytometry. (B) Quantification of infarct size of myocardial tissues 1 day after reperfusion. (C) Serum cTnT was measured 1 day after reperfusion. (D) Left ventricular ejection fraction (EF) and fractional shortening (FS) were measured via echocardiography 1 day after reperfusion (n = 5 per group). * $P < 0.05$ versus the other group.

Figure S3 Temporal changes of different signalling pathways in the ischaemic myocardium at different time points after reperfusion. Quantitative analysis of the phospho−/total-ERK, Akt, p38 MAPK, NF-κB p65, STAT1 and STAT3 levels in the myocardium at the indicated time points are shown (n = 6 per group). * $P < 0.05$ versus control.