

## Research Article

# Exosomes Released from CaSR-Stimulated PMNs Reduce Ischaemia/Reperfusion Injury

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Ischemia-reperfusion (I/R) injury caused by acute myocardial infarction (AMI) can initiate a strong inflammatory response. Polymorphonuclear cells (PMNs) are the most important inflammatory cells. Our previous studies found that the calcium-sensing receptor (CaSR) regulates the proinflammatory effects of PMNs. However, the role and mechanism of CaSR-regulated PMNs in I/R injury remain uncertain. A rat AMI model was developed in this study and showed that the expression of CaSR on PMNs increased in AMI; however, the levels of Bcl-x1 and SOD in myocardial tissue decreased, while Bax and MDA levels increased. Then, after coculture with CaSR-stimulated PMNs, the expression of Bcl-x1 in cardiomyocytes significantly increased, Bax expression and the apoptotic rate decreased, and ROS production was significantly inhibited. At the same time, the cardiomyocyte damage caused by hypoxia-reoxygenation was reduced. Furthermore, we found that exosomes derived from PMNs could be taken up by cardiomyocytes. Additionally, the exosomes secreted by CaSR-stimulated PMNs had the same effect on cardiomyocytes as CaSR-stimulated PMNs, while the increased phosphorylation level of AKT in cardiomyocytes could be reversed by AKT transduction pathway inhibitors. Subsequently, we identified the exosomes derived from CaSR-stimulated PMNs by second-generation sequencing technology, and increased expression of lncRNA ENSRNOT00000039868 was noted. The data show that this lncRNA can prevent the hypoxia-reoxygenation injury by upregulating the expression of PDGFD in cardiomyocytes. In vivo, exosomes from CaSR-stimulated PMNs played a significant role against AMI and reperfusion injury in myocardial tissue. Thus, we propose that exosomes derived from CaSR-stimulated PMNs can reduce I/R injury in AMI, and this effect may be related to the AKT signaling pathway.

## 1. Introduction

Acute myocardial infarction (AMI) is one of the main causes of human death worldwide, and reperfusion is the main clinical treatment. However, ischaemia-reperfusion (I/R) injury was first used to describe a phenomenon that reperfusion itself exacerbates myocardial injury in 1960 [1]. A lot of researches also have shown that the reperfusion process itself can cause irreversible extra damage to the myocardial [2]. It has been reported that leukocytes, especially polymorphonuclear neutrophils (PMNs) in the circulatory system, can damage the tissue after myocardial ischaemia/reperfusion by enhancing the release of various enzymes and cytokines [3]. However, there are also some studies showing that PMNs

can have a protective role in some diseases. In acute lung injury, Neudecker et al. found that PMN-derived microRNA-223 could be transferred to alveolar epithelial cells and increased the expression of miR-223 in lung epithelial cells, thereby, reversing acute lung injury by inhibiting PARP-1 during PMN coculturing with lung epithelial cells in vitro or after ventilator-induced acute lung injury in mice [4]. However, it has not been reported whether PMNs have protective effects on myocardial tissue. Knowing how to regulate inflammation reactions and the functions of PMNs in myocardial ischaemia and reperfusion to prevent myocardial tissue from injury is important.

The calcium-sensing receptor (CaSR) belongs to family C of the G-protein coupled receptors. CaSR has been shown to

be involved in modulating inflammation reactions in many cells and tissues [5]. In LS14 preadipocytes, CaSR has been shown to activate NLRP3 to enhance caspase-1 activation and IL-1 $\beta$  secretion mediated by the ERK1/2 signaling pathway, and CaSR-dependent NLRP3 inflammasome activation in preadipocytes through ERK signaling may favoring the cardiovascular system [6]. In our previous studies, CaSR was shown to modulate the inflammation reaction in T lymphocytes through the NF- $\kappa$ B signaling pathway [7]. We also found that the expression of CaSR increased after PMNs were activated by N-formyl-Met-Leu-Phe (fMLP) and platelet activating factor (PAF), and CaSR can promote proinflammatory effect and extending lifespan in PMNs [8].

Cell-to-cell communication is important to maintain tissue homeostasis and response to some exogenous stimuli. In AMI, the effects of PMNs on cardiomyocytes can occur through various mechanisms, such as exosomes (EXOs). EXOs are particles ranging from 40 nm to 100 nm that are released by cellular endosomes and have an important effect on cell-to-cell contact. There is a variety of proteins, DNA, mRNA, and noncoding RNA in exosomes [9], and cells in normal and pathogenic conditions can release exosomes containing different contents. Exosomes originating from the heart have specific proteomic markers [10, 11]. In AMI, cardiac exosomes and the exosomes released by injured cardiomyocytes, which contain cardiac-specific miRNAs, can be used as markers of myocardial injury, and they are enriched in factors that can promote angiogenesis, antiapoptosis, and cell growth, thereby, inducing repair and healing of infarcted myocardium [12]. In severe corticosteroid-insensitive asthmatic patients, exosomes released by activating PMNs can enhance the proliferation capability of airway smooth muscle and promote airway remodeling [13]. Exosomes obtained from AKT-modified human umbilical cord mesenchymal stem cells are highly effective at promoting angiogenesis in myocardial infarction therapy, and platelet-derived growth factor D (PDGFD) in the exosomes also plays a crucial role in angiogenesis [14].

PDGFD, a member of the PDGF family, was recently discovered to play a significant role in the response to injury, such as angiogenesis, vessel remodeling, inflammation, and repair [15]. Highly expressed PDGFD has been detected in both the adult and mouse hearts [16]. Tratwal and other researchers also found that when adipose tissue-derived stromal cells were stimulated by serum deprivation, the expression of growth factors such as PDGFD and FGF9 in the cells was increased, which was beneficial to myocardial protection, extracellular matrix remodeling, and angiogenesis-related late-stage maturation of infarct healing [17]. Therefore, PDGFD was associated with myocardial protection.

It is well known that PMNs play an important role in myocardial ischaemia/reperfusion injury. PMNs can infiltrate the myocardium and secrete a variety of proinflammatory factors that cause severe irreversible damage to the myocardium [3]. However, the mechanisms of action of PMNs on cardiomyocytes, especially something in PMNs, are beneficial in an injury caused by PMNs after myocardial ischaemia/reperfusion remains unknown.

## 2. Materials and Methods

**2.1. Materials.** Antibodies recognizing CD9, CD63, Grp-78, AKT, p-AKT, Bcl-2, Bcl-xl, Bax, and Nox2 were purchased from Cell Signaling Technology (Boston, USA), CaSR was purchased from Novus (Colorado, USA), and PDGFD was purchased from Abcam (Cambridge, UK). Histopaque 1083, Histopaque 1119, PKH67 green fluorescent labeling kit, and platelet activating factor (PAF) were purchased from Sigma (Darmstadt, Germany). The DHE-ROS kit was from BestBio (Shanghai, China). NPS-2143, cinacalcet, and HY-15186 were purchased from MCE (New Jersey, USA).

**2.2. Primary Cardiomyocyte Cultures.** Neonatal Wistar rats (0 to 2 days) were sterilized with 75% ethanol as previously described [18]. The myocardial tissue was digested with 7 mL of trypsin containing 0.1% collagenase I at 37°C for 7 min, and the supernatant was discarded. The last step was repeated, but the supernatant was collected and transferred to a new 50 ml centrifuge tube with 7 ml DMEM containing 10% FBS (CellMax, China). The myocardial tissue was handled four times, as in the last step. The suspension in each tube was cultured into 100 mm culture dishes for 2 hours. The cardiomyocytes in the supernatant were collected by centrifugation. The resulting pellet was cultured in a 5% CO<sub>2</sub> cell culture incubator at 37°C for 4-6 days.

**2.3. Induction of AMI and the Ischaemia/Reperfusion Model.** The myocardial AMI and I/R rat model was induced by ligating/perfusing the left anterior descending coronary artery (LAD) as previously described [19]. According to the reports, 50% infarct size is acceptable in these models [20]. All of the Wistar rats (200-250 g) were maintained under specific pathogen-free conditions in the Animal holding Units. This study was performed in strict accordance with the recommendations and experimental protocol approved by the Institute Animal Care and Use Committee (IACUC) at the Harbin Medical Experimental Animal Care Commission, China. The ribs and left anterior descending (LAD) artery were exposed. The ligation line that was previously placed around the LAD was tightened to completely occlude the blood vessel for ischaemia as an AMI group; the sham group animals underwent the same surgery apart from the ligation of the LAD suture. After 30 min, the ligation line was loosened to reperfuse the coronary arteries for 24 hours as the ischaemia/reperfusion group.

**2.4. Cardiomyocyte Hypoxia/Reoxygenation Experiments.** Wistar neonatal rat cardiomyocytes were subjected to H/R to imitate myocardial I/R injury as previously described [21]. Cardiomyocytes are divided into hypoxia group and hypoxia-reoxygenation group. The cardiomyocytes in D-Hanks solution were placed in a hypoxic atmosphere (5% CO<sub>2</sub> and 95% N<sub>2</sub>) to achieve hypoxia. Reperfusion was replicated by transferring neonatal rat cardiomyocytes after hypoxia to DMEM medium with 10% FBS and incubating in normoxic conditions (95% air and 5% CO<sub>2</sub>) to achieve reoxygenation. The cardiomyocytes underwent 4 hours of hypoxia to mimic ischaemia and 24 hours of reoxygenation to mimic reperfusion.

**2.5. PMN Isolation.** Whole blood from adult Wistar rats (200–250 g) anticoagulated with EDTA was collected and centrifuged at  $1500 \times g$  for 15 min. The leukocyte-rich cell layer was transferred to a new 15 ml tube and suspended in 2 ml of D-Hanks solution. The cell suspension was carefully loaded on top of 2 ml Histopaque 1119 and 2 ml Histopaque 1083 density gradients and centrifuged at  $700 \times g$  for 30 min at  $20^\circ\text{C}$ . The PMNs were collected in the layer between the Histopaque 1083 and 1119, and then the cells were suspended in 2 ml of D-Hanks and centrifuged at 1000 rpm for 10 min. The PMNs were resuspended in RPMI 1640 with 10% FBS, and the viability and purity of the cells were determined by trypan blue dye exclusion and Wright-Giemsa staining. PMN viability and purity exceeded 95% for follow-up experiments. The PMNs were stimulated with fMLP (10 nM) for 2 min and were incubated for 30 min at  $37^\circ\text{C}$  after induction with the CaSR inhibitor NPS-2143 (100 nM) and activator cinacalcet (100 nM). Then, the inhibitor or activator was replaced with fresh culture medium, and the PMNs were cocultured with cardiomyocytes.

**2.6. PMN-Derived Exosome Isolation.** PMNs were cultured in RPMI 1640 with 10% exosome-depleted FBS for 24 hours in order to eliminate the exosome impact in FBS. Then, after these PMNs were centrifuged at  $300 \times g$  for 10 min,  $2000 \times g$  for 10 min and  $10000 \times g$  for 30 min, and ultracentrifuged at  $100,000 \times g$  for 70 min, the pellets were collected and resuspended. And then, the exosomes were collected after another ultracentrifugation of these pellets at  $100,000 \times g$  for 70 min and then suspend the exosomes in PBS [22]. Exosomes were quantified by the BCA method. The purity of the exosomes was examined by tunable resistive pulse sensing (TRPS) [23], electron microscopy, and western blot.

**2.7. Exosome Uptake Experiment.** Exosomes isolated from PMN medium or PMNs were labeled with a PKH67 green fluorescent labeling kit (Sigma) according to the manufacturer's instructions. Divide cardiomyocytes into three groups and coculture with PKH-67 labeled PMNs, exosomes, and GW4869-treated PMNs. PMNs and PMN-derived exosomes were labeled with PKH-67 for 3 min at room temperature. Then, the cells were incubated with exosome-free serum to stop the staining. The exosomes were washed with a 100 kDa Amicon Ultra-4 ultrafiltration tube to remove excess dye and cocultured with cardiomyocytes for 24 hours. Fluorescence microscopy was used to observe the uptake of PMN exosomes by cardiomyocytes.

**2.8. siRNA Transfection.** According to the transfection procedure of the Lipo Fiter instruction manual [24], lncRNA 39868 interference sequence and nonsense sequence (siRNA-negative control) were transfected into rat primary cardiomyocytes. Total RNA was extracted after transfection. The expression of lncRNA 39868 mRNA was detected by qRT-PCR.

**2.9. Detection of Apoptosis.** The cells were incubated with  $5 \mu\text{l}$  Annexin V-fluorescein isothiocyanate (FITC) for 15 min at room temperature in the dark after being washed with D-Hanks, and then  $5 \mu\text{l}$  propidium iodide (PI) staining reagent

was added. Flow cytometry (BD LSRF Ortessa, USA) was used to measure the apoptosis rate of cardiomyocytes.

**2.10. Reactive Oxygen Species Assay.** The DHE-ROS kit from BestBio (Shanghai, China) was used to examine the generation of ROS according to the manufacturer's instructions. The cardiomyocyte suspension was stained with dihydroethidium (DHE) at 1 : 100 and seeded in a 96-well plate. The fluorescence intensity was measured by a fluorescence plate reader at an excitation wavelength of 490 nm and an emission wavelength of 525 nm.

**2.11. Myocardial Infarct Size Measurement.** Equivalent volumes of  $400 \mu\text{g}$  of exosome proteins were injected consecutively for seven days through the rat tail vein after AMI and I/R to observe the exosome function. I/R injury was detected by Evans blue/triphenyl tetrazolium chloride (TTC) double staining as previously described by Liu et al. [25]. The rat hearts were transected along the atrioventricular sulcus at the infarct zone after staining with Evans blue. The left ventricle (LV) was separated from the remaining part of the heart, cut into 3 mm thick sections, and weighed. The tissues were stained with 1% TTC in PBS. After that, the normal area was stained blue, the infarct zone was white, and the viable myocardium was red. The infarct size was analyzed by ImageJ. The unstained portion (area at risk; AAR), the Evans blue-stained portion (area not at risk; ANAR), the TTC-stained area (red), the TTC-negative stained area (white; infarcted myocardium), and the infarcted myocardium size are expressed as the percentage of myocardial necrosis to the ischaemic area at risk AAR.

**2.12. Detection of Cardiac Function.** Equivalent volumes of  $400 \mu\text{g}$  of exosome proteins were injected consecutively for seven days through the rat tail vein after AMI and I/R to observe the exosome function. The echocardiography analysis was studied using an echocardiography with a 20.0 MHz probe (GE ViVid 7.0, USA). The left ventricular ejection fraction (LVEF) and left ventricular fractional shortening (LVFS) were measured. All results were obtained from five consecutive cardiac cycles. After the echocardiography analysis is completed, insert the cannulation into the left ventricle through the right carotid artery of rats in advance. The cannulation is connected to the RM6240 multichannel physiological signal acquisition and processing system to record the following parameters, including left ventricular systolic pressure (LVSP), left ventricular developed pressure (LVDP), the maximal ventricular pressure rise ratio during the systolic period ( $+\text{dp}/\text{dt}_{\text{max}}$ ), and the maximal ventricular pressure decrease ratio during diastolic period ( $-\text{dp}/\text{dt}_{\text{max}}$ ).

**2.13. Statistical Analysis of Data.** All experiments were replicated at least three times. The values are expressed as the means  $\pm$  SD. Statistical significance among group means was assessed by Prism GraphPad 5.0. Comparisons of parameters were analyzed by one-way ANOVA followed by a Newman-Keuls post hoc test; differences were considered significant at  $P < 0.05$ .



### 3. Results

**3.1. The Expression of the CaSR on PMNs Increased in AMI Models.** In our previous studies, we demonstrated that the expression of the CaSR was elevated in activated PMNs, and in turn, the elevated CaSR expression enhanced the PMN immune effect. In this study, CaSR proteins with two relative molecular weights of 150 kDa and 130 kDa were detected. The CaSR levels increased significantly in both the AMI and I/R groups but did not change in the sham surgery group, as shown by Western blotting (Figure 1).

**3.2. CaSR-Stimulated PMNs Significantly Decreased Apoptosis and ROS Production of Cardiomyocytes after H/R Injury.** We further wanted to investigate the role of the CaSR on the PMNs in cardiomyocytes incubated under hypoxia and hypoxia/reoxygenation (H/R) conditions imitating ischaemia and reperfusion, so we cocultured these two types of cells indirectly. Cocultivation filters were used to separate the PMNs and cardiomyocytes (Figure 2(a)). First, we found that hypoxia and H/R elevated the levels of Bax but reduced the levels of Bcl-xl in cardiomyocytes. Then, we found that PMNs and fMLP-activated PMNs decreased the expression of Bcl-xl, while the expression of the proapoptotic protein Bax was increased. However, PMNs activated by the CaSR activator cinacalcet increased the Bcl-xl levels but decreased the Bax expression levels in cardiomyocytes under hypoxia/reoxygenation conditions. Treatment with the CaSR inhibitor NPS2143 had the opposite effect. The ratio of Bcl-xl and Bax proteins better reflected the above situation (Figure 2(b)).

The apoptosis rate of cardiomyocytes was detected by flow cytometry. The results showed that the apoptosis rate of cardiomyocytes was increased after hypoxia and hypoxia/reoxygenation, and cardiomyocytes displayed significantly increased apoptosis after coculturing with PMNs during reoxygenation. However, coculture with CaSR-inhibited PMNs raised the cardiomyocyte apoptosis rate to nearly 95%, which was reversed by CaSR-stimulated PMNs (Figure 2(c)).

Nox2 and ROS are indicators of cell oxidative damage and are found at low levels in normal cardiomyocytes. In our study, Nox2 and ROS increased when cardiomyocytes were subjected to hypoxia and hypoxia/reoxygenation and significantly increased after coculture with PMNs and activated PMNs. Furthermore, the production of Nox2 and ROS was markedly increased when PMNs were treated with the CaSR inhibitor NPS-2143, and the opposite results were obtained when PMNs were treated with the CaSR activator cinacalcet (Figures 2(d) and 2(e)).

**3.3. Characterization of PMN-Derived Exosomes.** In order to test whether PMNs can secrete exosomes, we extracted the vesicles from the PMN supernatant by ultracentrifugation. The exosome surface marker CD9 and CD63 and the endoplasmic reticulum marker Grp78 were detected by increasing the total amount of protein loading to 40  $\mu$ g. We found that the supernatant extract contained high levels of CD9 and CD63 without Grp78, whereas Grp78 was highly expressed in cell lysates (Figure 3(a)). The size distribution profile dis-

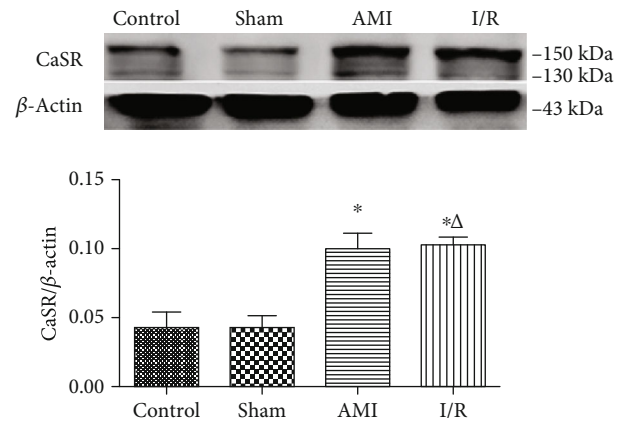


FIGURE 1: CaSR expression on rat peripheral blood PMNs. The expression of the CaSR on PMNs increased when AMI and I/R occurred. Data are shown as the means  $\pm$  SD; \* $P < 0.05$  vs. the sham group,  $\Delta P < 0.05$  vs. the AMI group. Data are from three independent experiments.

played a population ranging from 50 to 100 nm, which is exactly the exosome size range (Figure 3(b)). Extracellular vesicles (EVs) with the typical cup-shape and double membrane structure as exosomes were detected by transmission electron microscopy (Figure 3(c)). All these results demonstrate that PMNs can secrete exosomes; the size distribution and shape image indicated the high purity of exosomes.

**3.4. GW4869 Inhibited PMN Function.** To clarify whether exosomes from CaSR-stimulated PMNs are involved in the effects of reduce apoptosis rate on cardiomyocytes. We treated PMNs and PMN-derived exosomes labeled with PKH-67 with/without the exosome inhibitor GW4869 and cocultured the PMNs with cardiomyocytes. Green fluorescence appeared in cardiomyocytes cocultured with PMNs and PMN-derived exosomes, while no fluorescence was detected in cardiomyocytes cocultured with PMNs treated with GW4869 (Figure 4(a)). This result indicates that PMN-derived exosomes can be taken up by cardiomyocytes. After hypoxia-reoxygenation treatment, the apoptosis rate of cardiomyocytes increases. Subsequently, when the CaSR activator cinacalcet was used, the CaSR-stimulated PMNs reduced cardiomyocyte apoptosis, which was reversed by GW4869 (Figure 4(b)).

**3.5. The Exosomes from CaSR-Stimulated PMNs Significantly Inhibited Cardiomyocyte Apoptosis and ROS Production upon H/R Injury.** To further confirm whether PMNs-derived exosomes determine the functional impact of PMNs on cardiomyocytes, we cocultured 100  $\mu$ g of PMN-derived exosomes with cardiomyocytes subjected to reoxygenation after hypoxia for 4 hours. We found that the expression of p-AKT/AKT and Bcl-xl/Bax was reduced after H/R, whereas PMN-derived exosomes had no effect on these proteins. In contrast to the above results, the expression of all of these proteins was elevated by the CaSR agonist cinacalcet, which was inhibited by the AKT inhibitor HY15186 in cardiomyocytes (Figure 5(a)).

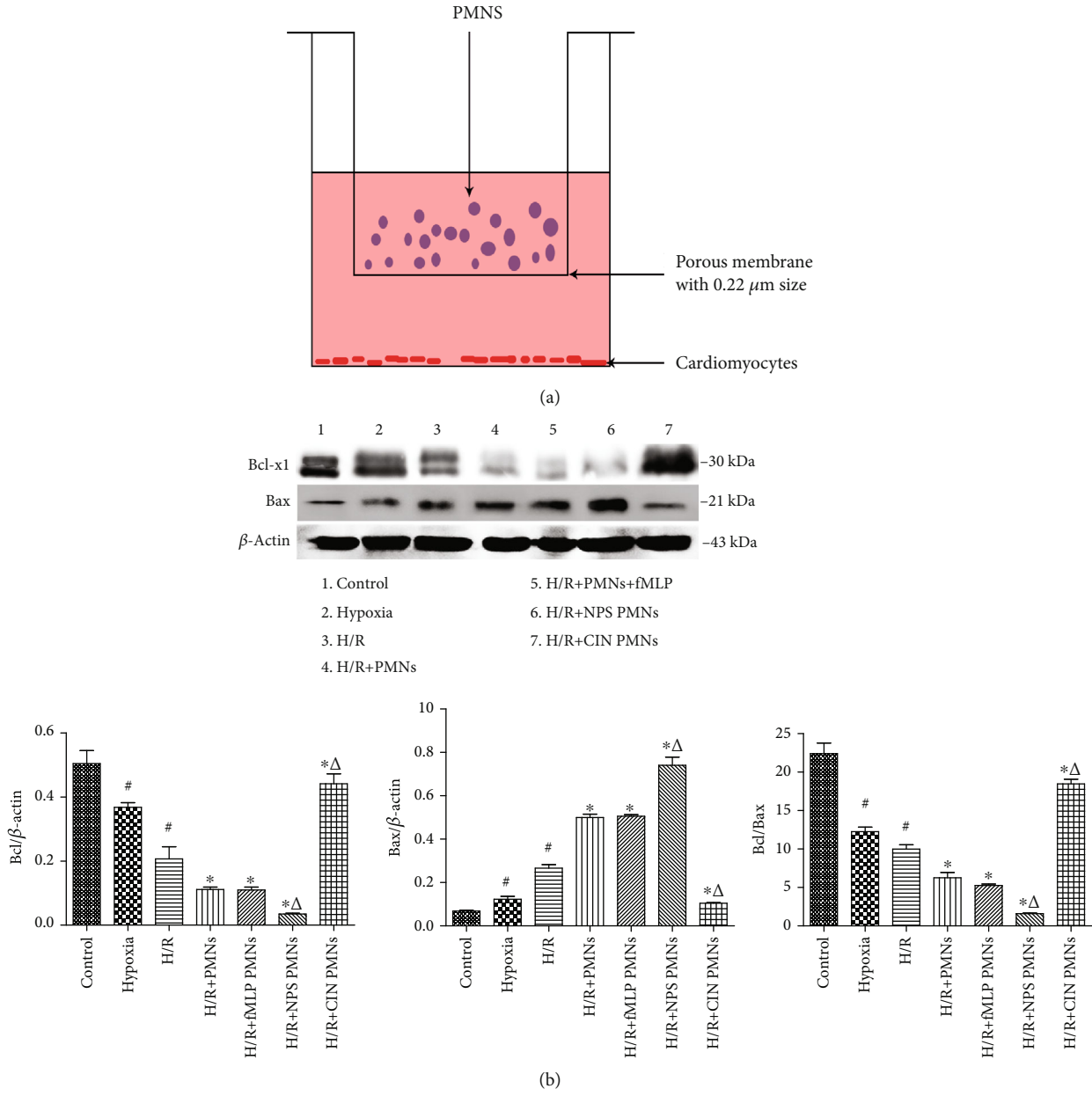
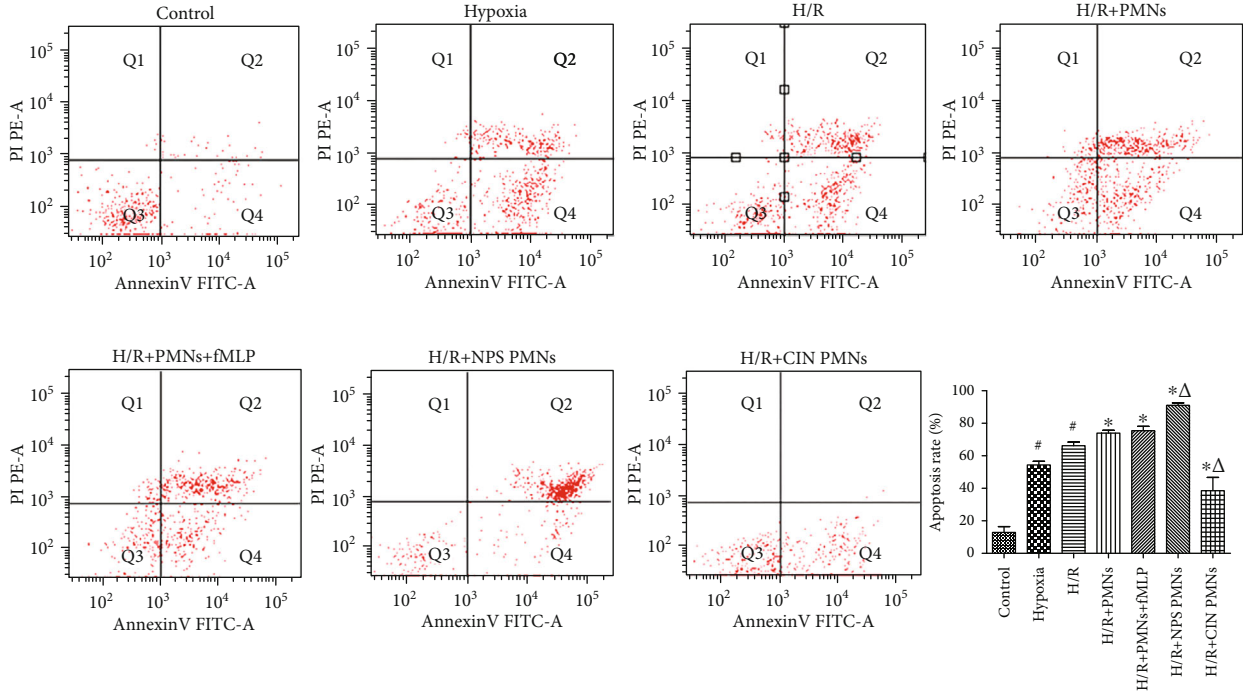
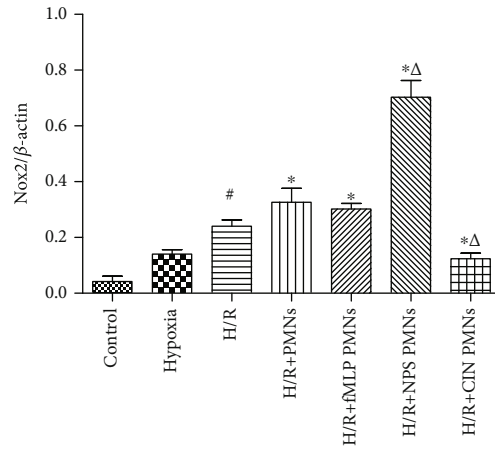
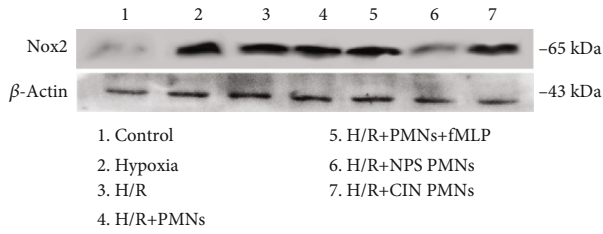


FIGURE 2: Continued.



(c)



(d)

FIGURE 2: Continued.

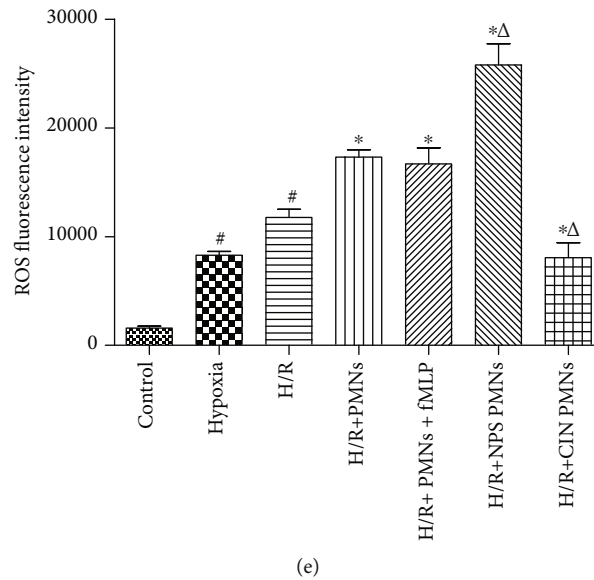


FIGURE 2: CaSR-stimulated PMNs significantly decreased apoptosis of cardiomyocytes in response to H/R injury. (a) The schema for PMNs coculturing with cardiomyocytes. (b) The expression of Bcl-xl and Bax was detected by western blot. (c) The cardiomyocyte apoptosis rates were detected. Q1: necrotic cells. Q2: late apoptotic cells. Q3: living cells. Q4: early apoptotic cells. The results are representative of three experiments, and the apoptosis rate under different conditions was quantified by densitometry. (d) Nox2 expression was detected by western blot. (e) The ROS content was measured by Fluorescent Probe DCFH-DA. Data are shown as the means  $\pm$  SD; \* $P$  < 0.05 vs. the control group, \* $P$  < 0.05 vs. the H/R group, and  $\Delta P$  < 0.05 vs. the H/R+PMNs group.

Similarly, we found that the apoptosis rate of cardiomyocytes was strongly increased during hypoxia-reoxygenation, and this increase was significantly reduced by exosomes derived from CaSR-stimulated PMNs (Figure 5(b)). Subsequently, we examined the influence of exosomes on oxidative stress in cardiomyocytes. The results showed that the levels of ROS and Nox2 in the H/R group were increased compared with those of the control group, and exosomes did not change this result. However, exosomes from CIN-activated PMNs reduced Nox2 expression and ROS production, which was reversed by the AKT transduction pathway inhibitor HY15186 (Figures 5(c) and 5(d)).

**3.6. CaSR Regulates the Expression of lncRNA ENSRNOT0000039868 in PMN-Derived Exosomes.** High-throughput sequencing was used to detect the differential expression of lncRNAs in exosomes secreted by CaSR-stimulated PMNs and untreated PMNs. The results suggested a significant difference between the two groups (Figures 6(a) and 6(b)). The CaSR activator cinacalcet significantly elevated the production of lncRNA ENSRNOT0000039868 (lncRNA 39868) in exosomes (the log<sub>2</sub>-fold change reached 5.69548), which was confirmed by qRT-PCR. The same change occurred with exosomes derived from PMNs activated by the PMN activator PAF. The CaSR inhibitor had the opposite effect (Figure 6(c)). In addition, the intake amount of lncRNA 39868 in cardiomyocytes increased in a coculture time-dependent manner (Figure 6(d)).

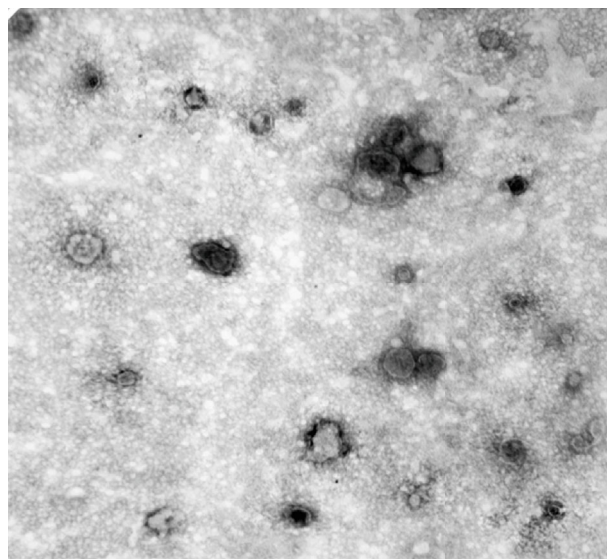
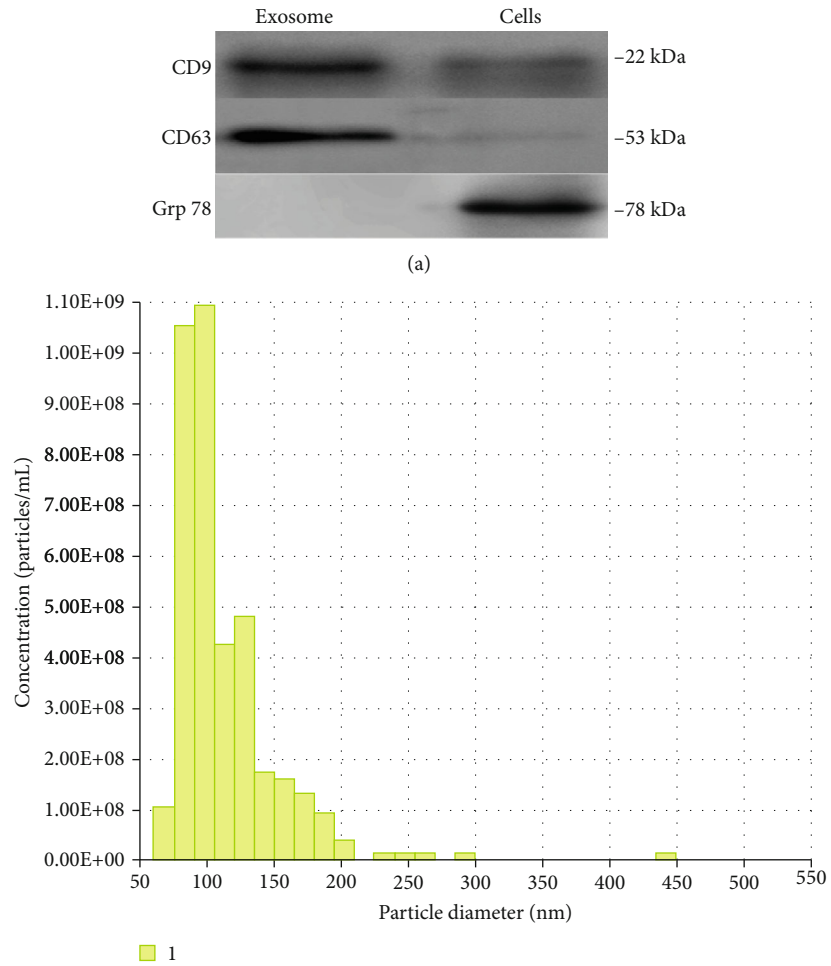
**3.7. Silencing lncRNA 39868 Decreases PDGFD Expression and Enhances Myocardial Hypoxia-Reoxygenation Injury.** PDGFD was predicted as a target protein of lncRNA 39868

by high-throughput sequencing. To verify this result, we silenced lncRNA 39868 in cardiomyocytes after they were cocultured with PMNs. The results showed that siRNA transfection strongly decreased the expression of PDGFD mRNA in cardiomyocytes (Figure 7(a)).

Next, we observed the role of lncRNA 39868 and PDGFD in cardiomyocytes. First, we found that the expression of both lncRNA 39868 and PDGFD decreased in hypoxic and H/R cardiomyocytes compared with normal cardiomyocytes. Due to the lack of significant difference between the hypoxia and H/R groups, H/R cardiomyocytes were selected for further research.

Then, we showed that normal and H/R cardiomyocytes, after they were cocultured with CaSR-stimulated PMN-derived exosomes, increased lncRNA 39868, PDGFD, and SOD activity and decreased of Bax/Bcl-2 ratio, ROS, MDA, TNF- $\alpha$  secretion, and cardiomyocyte apoptotic rate. Conversely, silencing lncRNA 39868 resulted in a decrease in PDGFD expression and SOD activity and an increase in ROS, MDA, and TNF- $\alpha$  secretion, the cardiomyocyte apoptotic rate, and Bax/Bcl-2 ratio (Figures 7(b)–7(f)).

**3.8. The Expression of PDGFD Is Associated with Myocardial Damage.** Based on the prediction by second-generation sequencing analysis, PDGFD was identified as a target protein of lncRNA 39868. Next, to determine whether PDGFD levels changed upon myocardium damage, we tested the expression of PDGFD in myocardial tissue and cardiomyocytes. The results showed that the expression of PDGFD was suppressed under AMI and I/R conditions (Figure 8(a)). Moreover, we found that under hypoxia and H/R conditions, the level of PDGFD in cardiomyocytes was reduced after



500 nm  
 HV = 80.0 kV  
 Direct Mag: 70000×

(c)

FIGURE 3: Characterization of PMN-derived exosomes. (a) The expression of the exosome marker CD9 and CD63 and the cell marker Grp78. (b) The size distribution of exosomes. (c) Exosomes isolated from PMNs visualized by transmission electron microscopy.



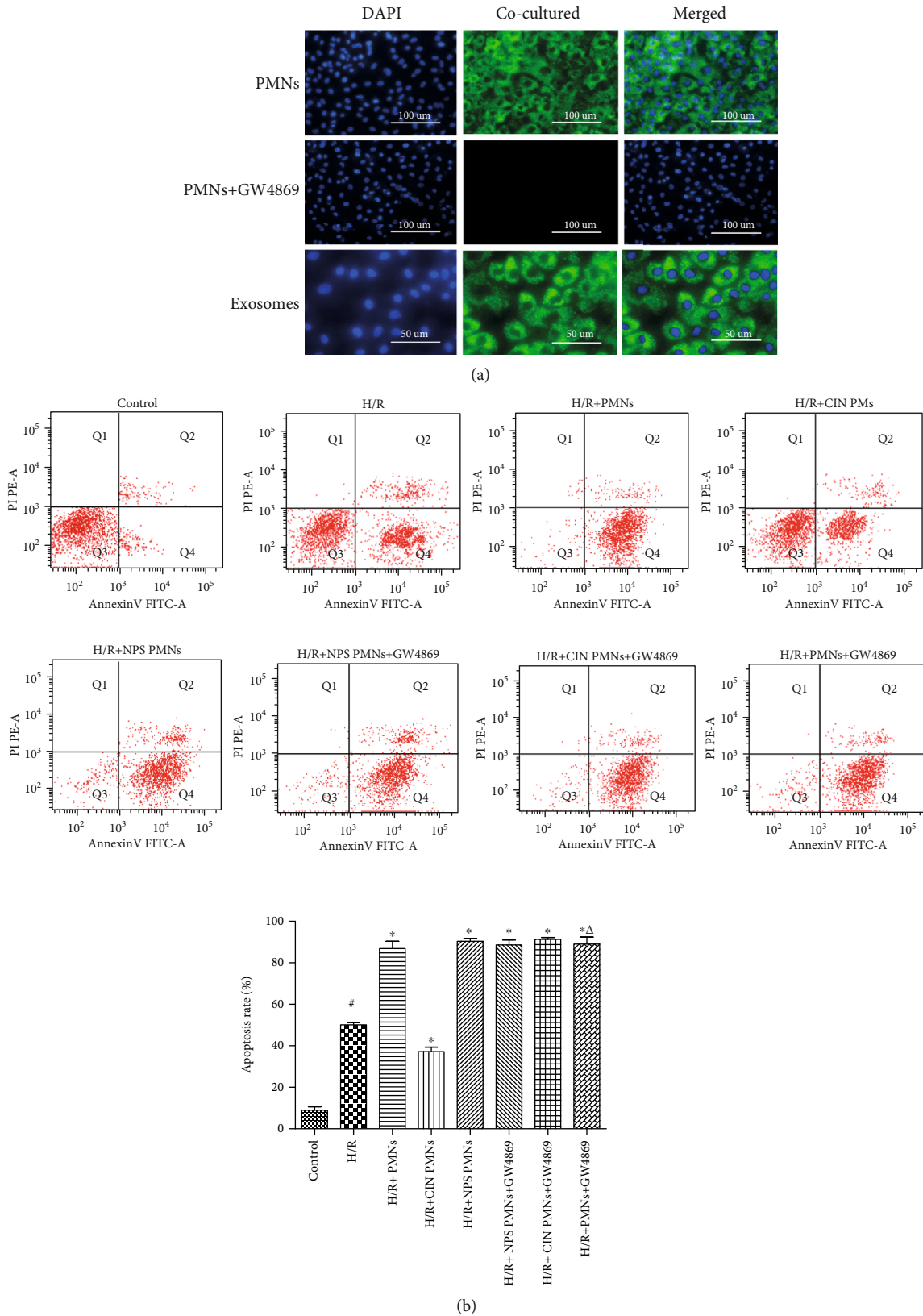


FIGURE 4: The effect of CaSR-stimulated PMN function can be inhibited by GW4869. (a) The results of green fluorescence in cardiomyocytes cocultured with PMNs and PMN-derived exosomes. (b) The apoptosis rate of cardiomyocytes. Q1: necrotic cells. Q2: late apoptotic cells. Q3: living cells. Q4: early apoptotic cells. Data are shown as the means  $\pm$  SD; # $P < 0.05$  vs. the control group, \* $P < 0.05$  vs. the H/R group, and  $\Delta P < 0.05$  vs. the CIN group. Data are representative of three independent experiments.

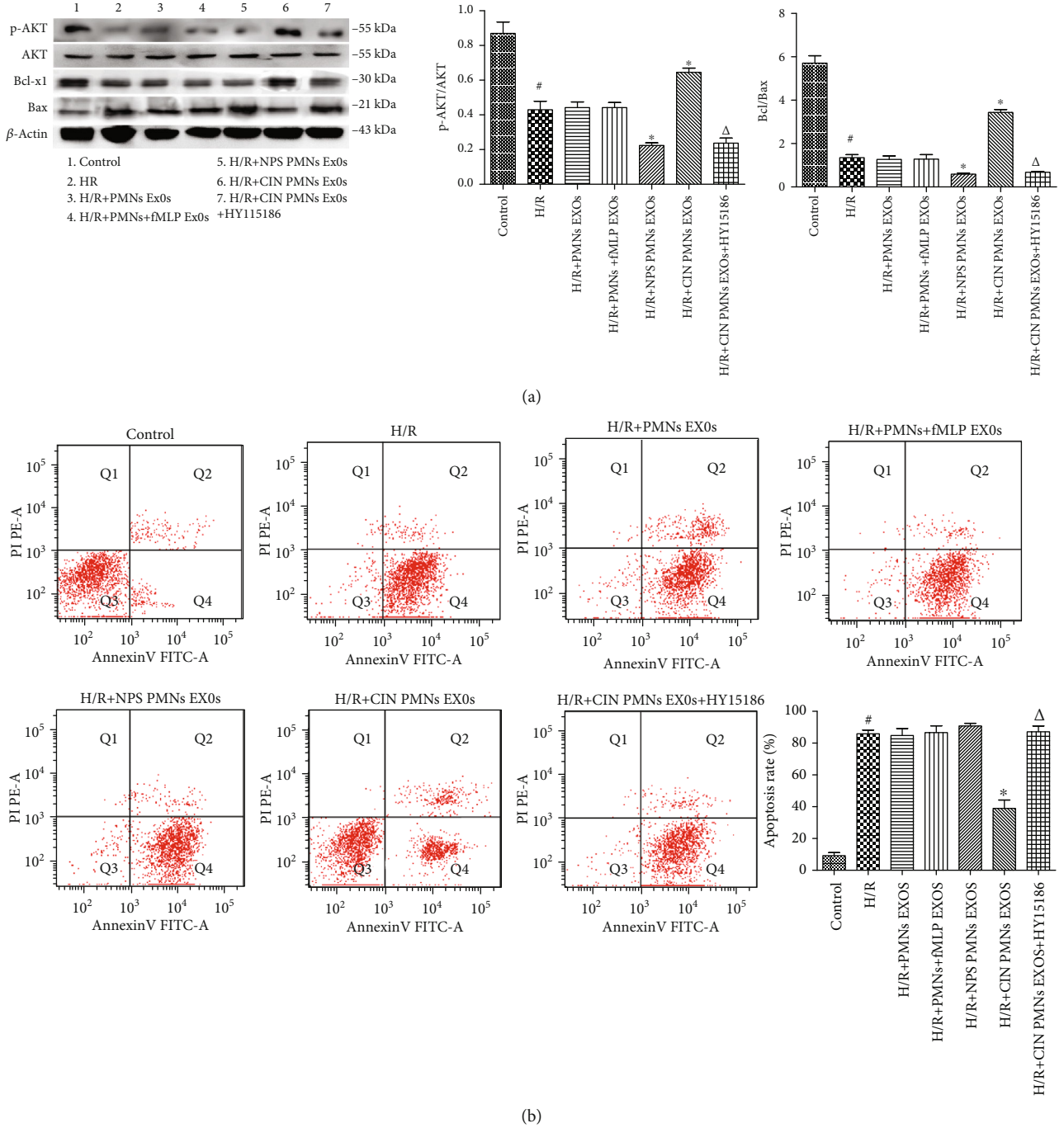


FIGURE 5: Continued.

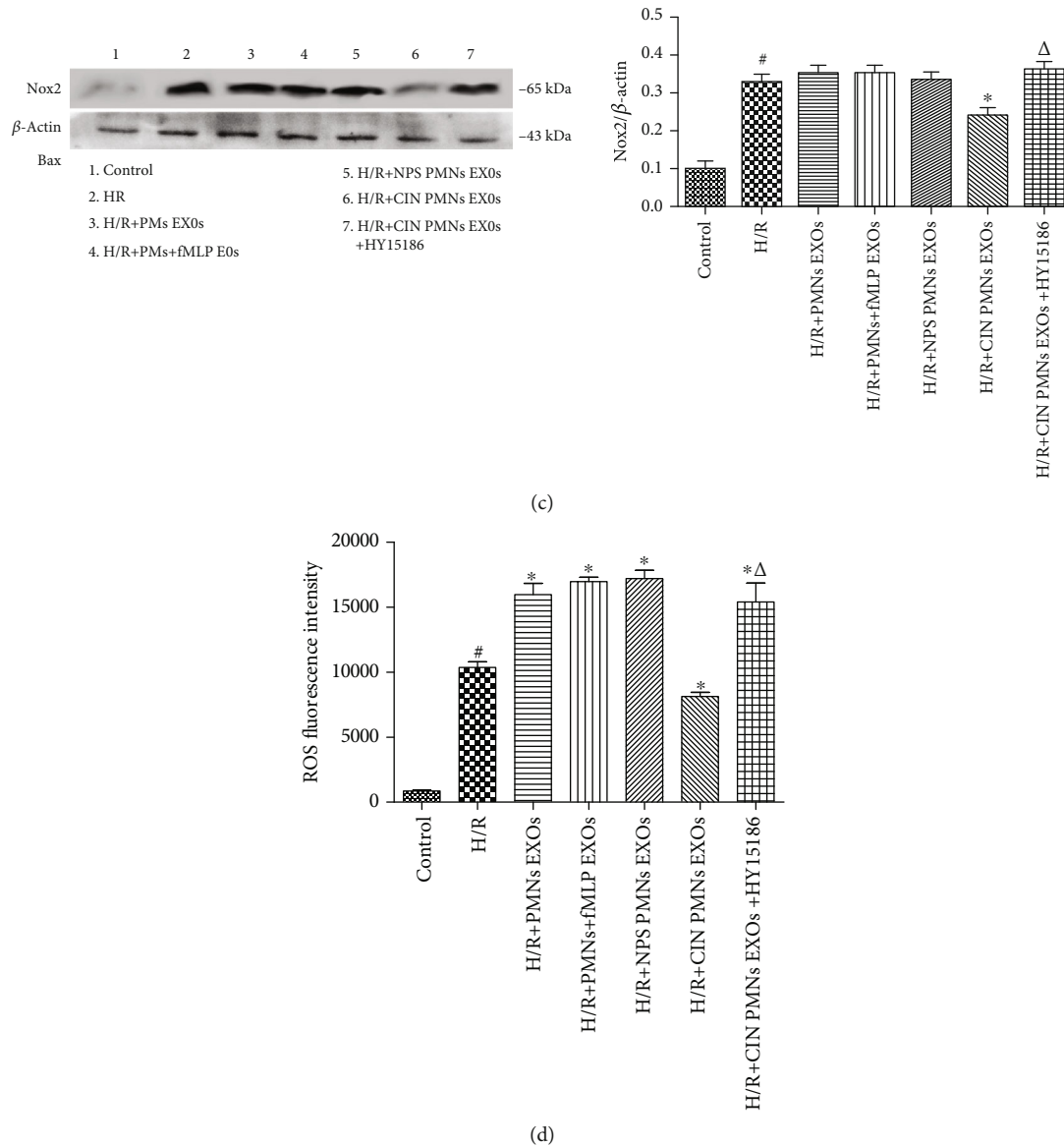


FIGURE 5: The exosomes from CaSR-stimulated PMNs significantly inhibited cardiomyocyte apoptosis after H/R injury. (a) In cardiomyocytes, the expression of p-AKT, Bcl-xl, and Bax after coculture with exosomes released from PMNs was detected by western blot. (b) The cardiomyocyte apoptosis rate was detected. The results are representative of three experiments, and the apoptosis rate under different conditions was quantified by densitometry. Q1: necrotic cells. Q2: late apoptotic cells. Q3: living cells. Q4: early apoptotic cells. (c) Exosomes from CaSR-stimulated PMNs decreased Nox2 expression and ROS production from cardiomyocytes during H/R injury. (d) Exosomes from CaSR-stimulated PMNs decreased ROS production in cardiomyocytes during H/R injury. Data are shown as the means  $\pm$  SD;  $^{\#}P < 0.05$  vs. control group,  $^*P < 0.05$  vs. H/R group, and  $^{\Delta}P < 0.05$  vs. CIN group. Data are representative of three independent experiments.

coculture with PMNs and was increased after coculture with CaSR-stimulated PMNs (Figure 8(b)). Furthermore, the exosome inhibitor GW4869 had the opposite effect. These findings demonstrate that exosome inhibition by GW4869 not only abolishes the effect of cinacalcet but also decreases PDGFD levels below those of the control group (Figure 8(c)). Subsequently, we obtained similar results after coculture of cardiomyocytes with exosomes secreted by PMNs, whereby the expression of PDGFD in cardiomyocytes was increased and could be suppressed by the AKT pathway inhibitor HY15186 (Figure 8(d)).

**3.9. Exosomes Derived from CaSR-Stimulated PMNs Reduced the Size of the Myocardial Infarction and Improved Heart Function In Vivo.** AMI and I/R models were developed. The exosomes were separately extracted from the culture supernatant of PMNs subjected to different treatments. After 400  $\mu$ g exosomes were injected continuously into the rat tail vein for 7 days, peripheral blood was obtained, and the myocardium was stained. The results showed that exosomes derived from CaSR-stimulated PMNs significantly reduced the infarct area of the myocardial tissue and the secretion of MDA and increased SOD levels. However, exosomes derived

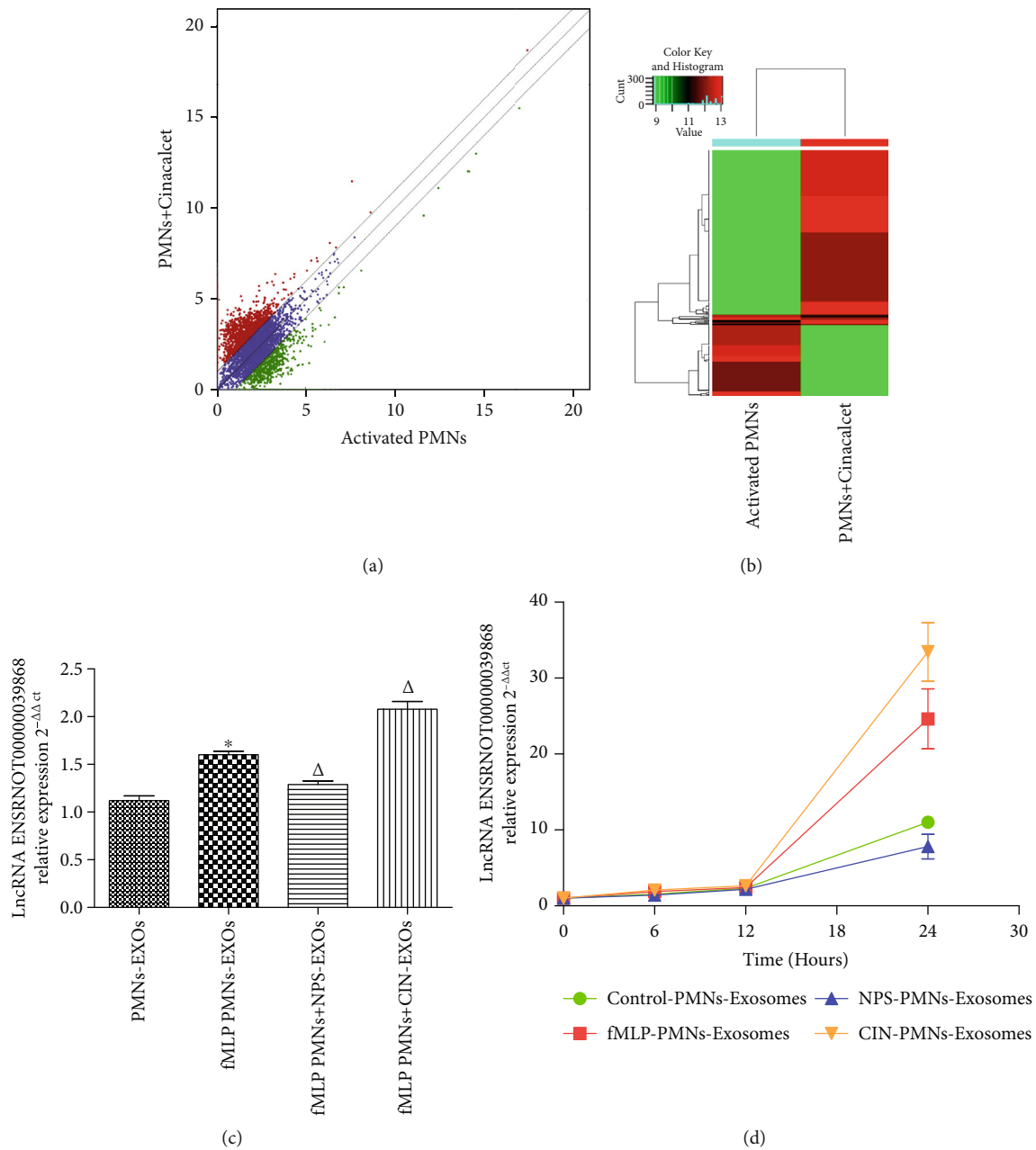


FIGURE 6: CaSR regulates the expression of lncRNA 39868 in PMN-derived exosomes. (a) High-throughput sequencing results of the lncRNA scatter plot. (b) High-throughput sequencing results of the lncRNA cluster analysis heat map. (c) CaSR regulates the expression of lncRNA 39868 in PMN-derived exosomes. (d) lncRNA 39868 expression increased in cardiomyocytes in a coculture time-dependent manner. Data are shown as the means  $\pm$  SD; \* $P < 0.05$  vs. PMNs Exosomes group,  $\Delta P < 0.05$  vs. fMLP PMNs Exosomes group. Data are representative of three independent experiments.

from CaSR-inhibited PMNs failed to exert an obvious influence on myocardial tissue injury (Figures 9(a) and 9(b)). As shown in Figures 9(c) and 9(d), compared with Sham rats, LVSP, +dp/dtmax, -dp/dtmax, LVFS%, and LVEF% of AMI and I/R rats decreased significantly with the increase of LVDP, and the changes in I/R rats are more obvious. But, in I/R and AMI rats injected with exosomes derived from CaSR-stimulated PMNs, LVSP, +dp/dtmax, -dp/dtmax, LVFS%, and LVEF% increased, but LVDP decreased. In addition, exosomes derived from

CaSR-inhibited PMNs had no significant effect on these parameters in rats (Figures 9(c) and 9(d)).

#### 4. Discussion

Increasing attention has been paid to the effects of inflammatory damage and the mode of action of PMNs in myocardial ischaemia-reperfusion. In this study, the role of PMNs in myocardial ischaemia-reperfusion affected by the CaSR was clarified. When CaSR activity in PMNs was increased, PMNs

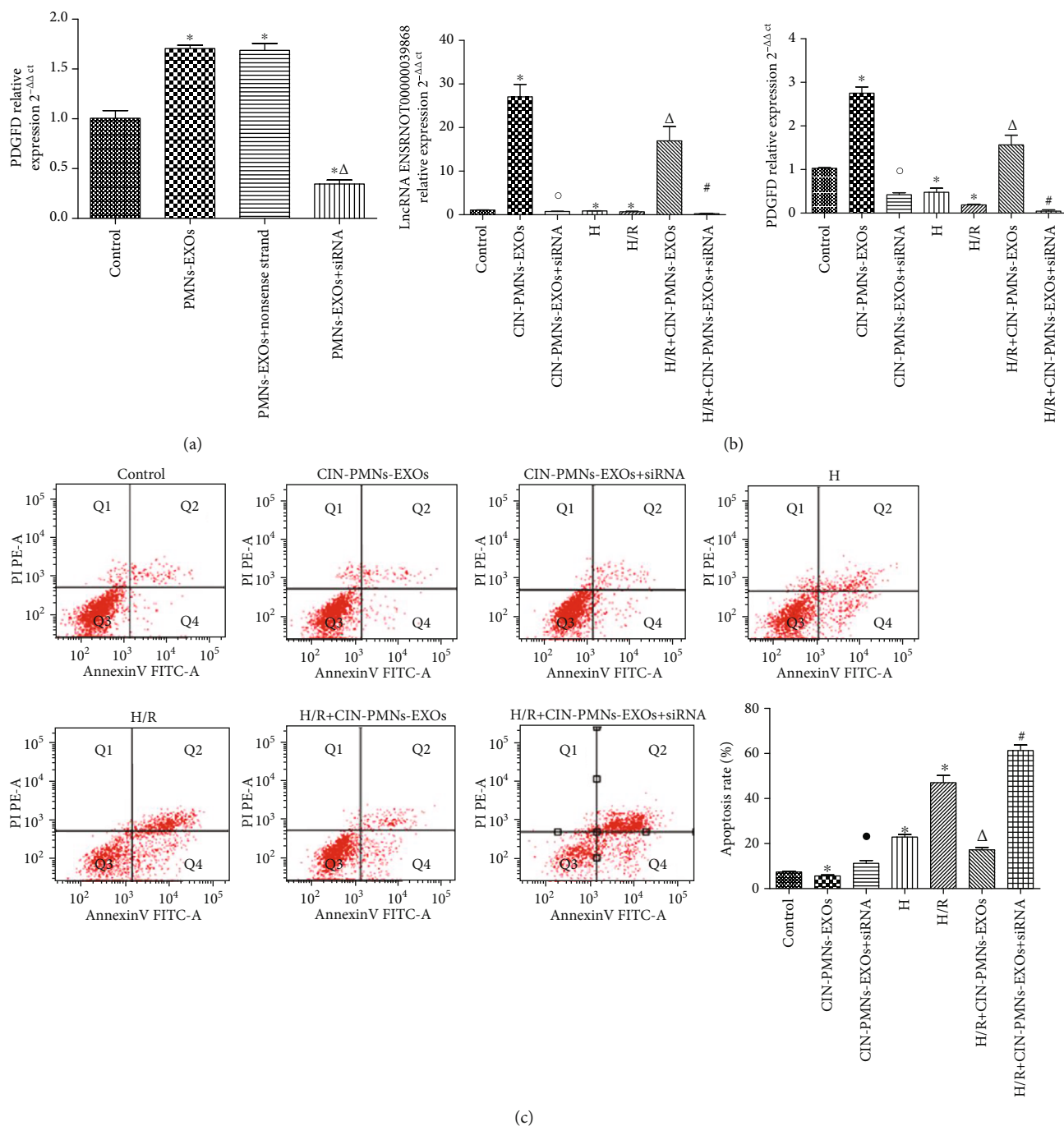


FIGURE 7: Continued.



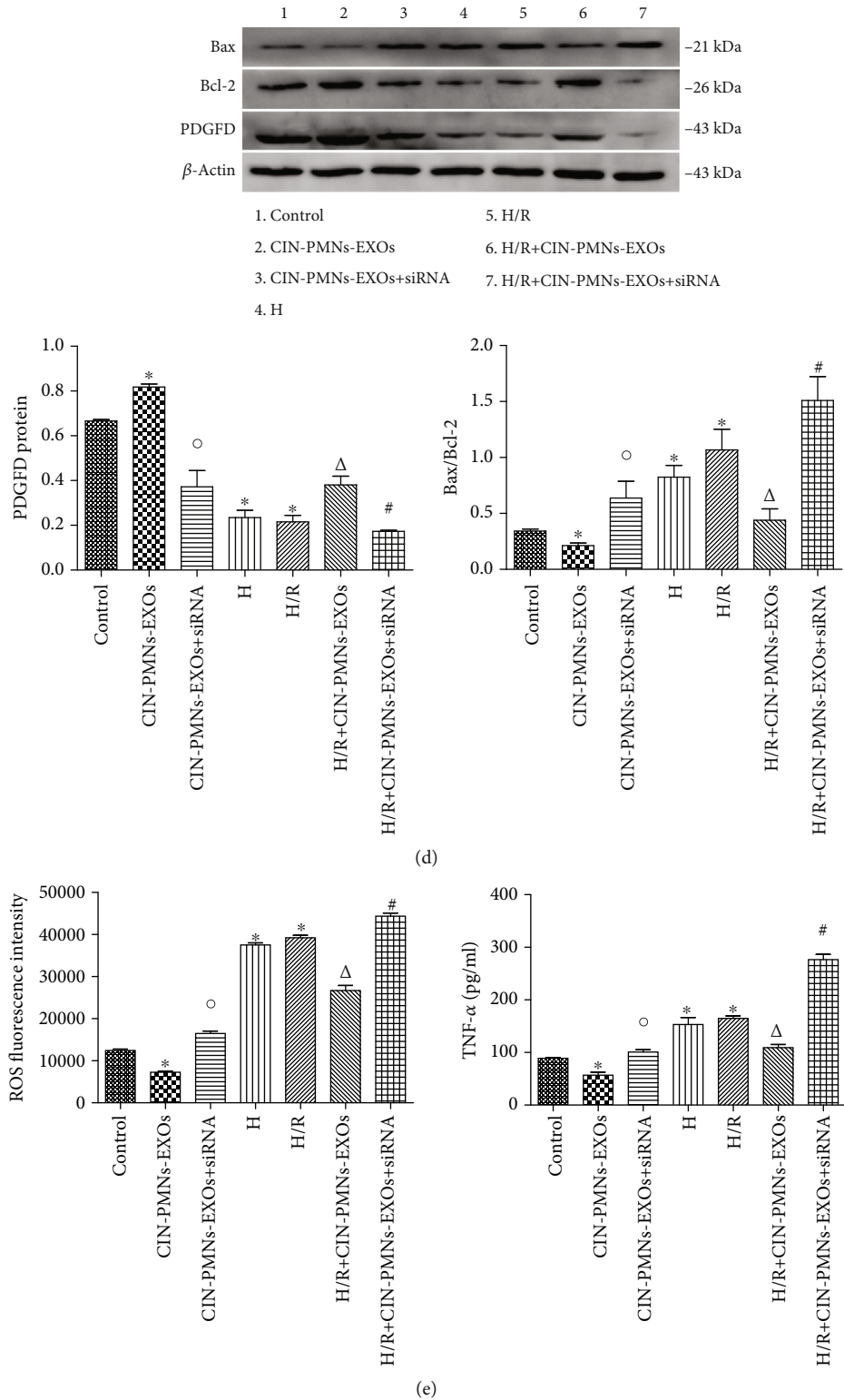


FIGURE 7: Continued.

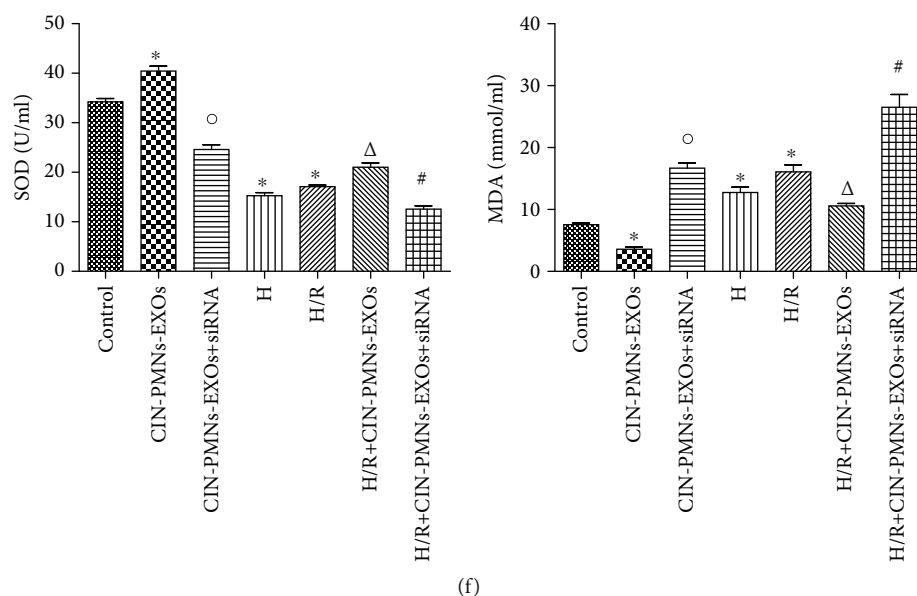


FIGURE 7: Effect of lncRNA 39868 silencing. (a) Silencing lncRNA 39868 inhibited the expression of PDGFD mRNA in cardiomyocytes. (b) CaSR-stimulated PMN-derived exosomes increased the expression of lncRNA 39868 and PDGFD, and silencing lncRNA showed the opposite results in cardiomyocytes. (c) The apoptotic rate of cardiomyocytes. (d) The expression of Bcl-2, Bax, and PDGFD in cardiomyocytes. (e) Expression of ROS and TNF- $\alpha$  in cardiomyocytes. (f) MDA and SOD levels in cardiomyocytes. Data are shown as the means  $\pm$  SD; \* $P < 0.05$  vs. control group,  $^{\Delta}P < 0.05$  vs. H/R group,  $^{\circ}P < 0.05$  vs. CIN-PMNs-EXOs group, # $P < 0.05$  vs. H/R + CIN-PMNs-EXOs +siRNA group. Data are representative of three independent experiments.

could reduce cardiac I/R injury and protect the myocardium via lncRNA 39868 in exosomes.

In our study, we first found that the expression of the CaSR increased in peripheral blood PMNs after acute myocardial infarction and ischaemia-reperfusion in rats. At the same time, the expression of proapoptotic protein Bax and MDA increased, while the expression of antiapoptotic protein Bcl-2 and SOD decreased (Supplementary Figures). These results show that rat myocardial tissue is significantly damaged after ischaemia-reperfusion.

In order to clarify the specific effects of the CaSR and PMNs on myocardial injury in rats after AMI and I/R, we cocultured rat peripheral blood PMNs and primary cardiomyocytes. The results showed that PMNs further decreased Bcl-xl levels and increased the Bax expression level after hypoxia and hypoxia-reoxygenation; the ratio of Bcl-xl/Bax showed a significant proapoptotic effect. However, treating PMNs with the CaSR-specific agonist cinacalcet reversed these results, which reveals that CaSR-stimulated PMNs can reduce cardiomyocyte injury.

Myocardial ischaemia-reperfusion injury increases ROS production and oxidative stress and accelerates the proinflammatory process and activation of cell death pathways [26]. Therefore, regulating the production of ROS is a promising approach for alleviating myocardial injury. In cardiomyocytes, ROS production is primarily regulated by Nox2 [27] and cleared by SOD [28]. Studies have reported that increasing the expression of Nox2 can enhance ROS production and ultimately enhance myocardial ischaemia-reperfusion injury, and this finding may be related to the activation of the AKT signal pathway [29]. In our experiments, after hypoxia-reoxygenation, the ROS content in cardiomyocytes increased; the

increase positively correlated with the expression of Bax, Nox2, and the rate of apoptosis. After hypoxia, cardiomyocytes were cocultured with PMNs stimulated with the CaSR activator cinacalcet during reoxygenation; ROS release was reduced, Nox2 and Bax were downregulated, and apoptosis was attenuated. These results further indicate that CaSR-stimulated PMNs can attenuate myocardial damage caused by ischaemia-reperfusion.

The above results showed that PMNs play a protective role against myocardial injury, which is different from our traditional opinion that PMNs promote inflammatory reactions, thereby, aggravating tissue injury. We hypothesized that certain substances must protect against the negative effects.

During the experimental process, we made an interesting observation. In our previous studies on the function of CaSR on PMNs, we found that the expression of CaSR was increased after PMNs were activated, and when PMNs were cocultured with cardiomyocytes, activated PMNs could not reduce cardiomyocyte apoptosis after hypoxia-reoxygenation. However, PMNs stimulated by cinacalcet can reduce cardiomyocyte apoptosis. Therefore, we speculate that PMNs have a dual role in promoting myocardial cell injury and repair in myocardial ischaemia-reperfusion injury. The specific role of PMNs in cardiomyocyte injury or repair is closely related to the degree of activation of CaSR. After PMNs are activated, the activation level of CaSR is not sufficient to prevent the inflammatory damage of the myocardium during myocardial ischaemia-reperfusion. After treatment with a CaSR agonist, the activity of CaSR was increased to a certain degree, and PMNs secreted various substances that participate in the repair process of myocardial hypoxia-reoxygenation.

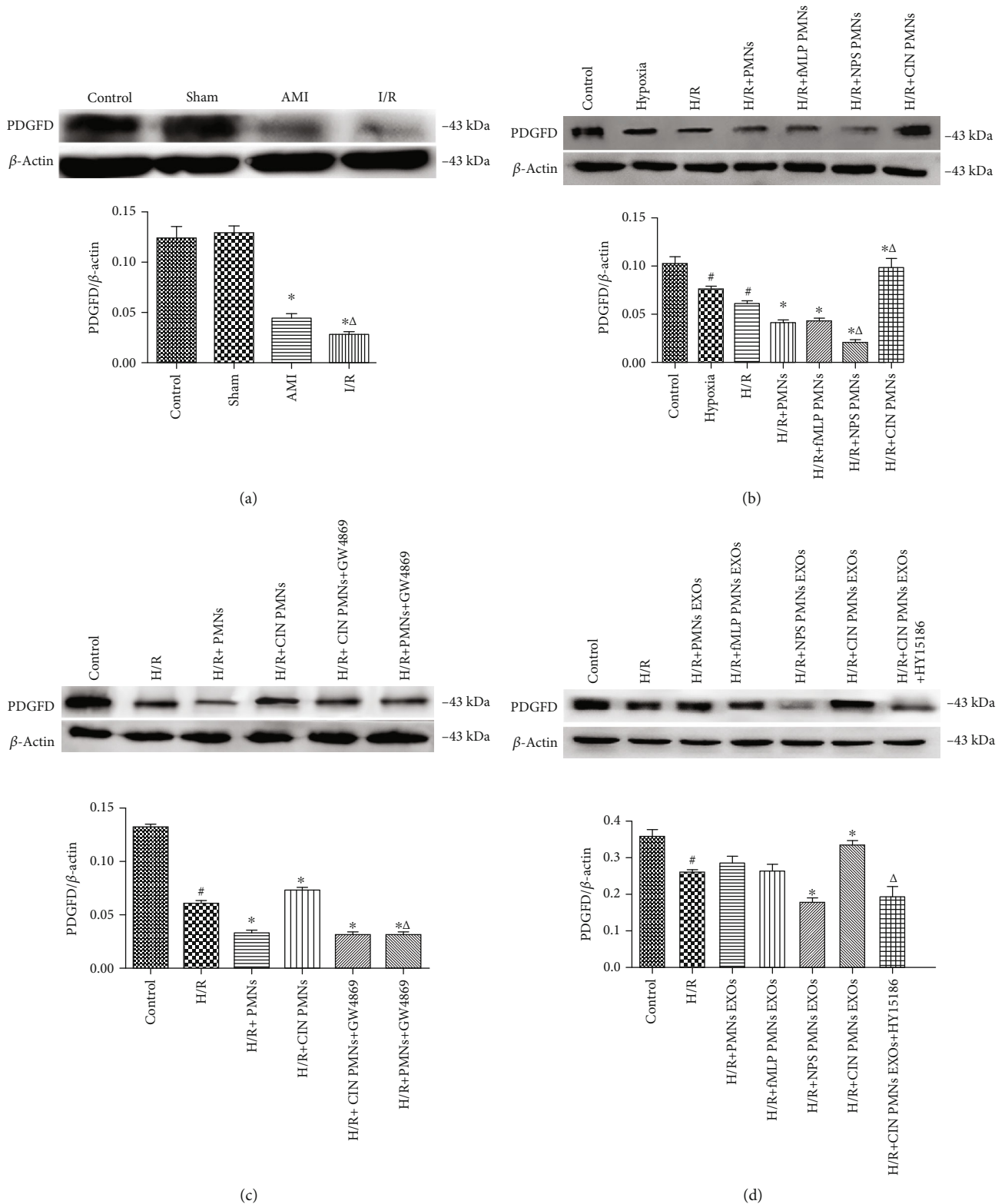


FIGURE 8: The exosomes from CaSR-stimulated PMNs significantly increased PDGFD levels in cardiomyocytes after H/R or I/R injury. (a) After myocardial tissue ischaemia and reperfusion, PDGFD protein levels were reduced in cardiac tissues. \* $P < 0.05$  vs. the sham group,  $\Delta P < 0.05$  vs. the AMI group. (b) The expression of PDGFD in cardiomyocytes after coculture with PMNs. \* $P < 0.05$  vs. the control group, \* $P < 0.05$  vs. the H/R group, and  $\Delta P < 0.05$  vs. the H/R+PMNs group. (c) PMN function can be inhibited by GW4869. \* $P < 0.05$  vs. the control group, \* $P < 0.05$  vs. the H/R group, and  $\Delta P < 0.05$  vs. the CIN group. (d) In cardiomyocytes, the expression of PDGFD after coculture with exosomes released from PMNs was detected by western blot. Data are shown as the means  $\pm$  SD; \* $P < 0.05$  vs. the control group, \* $P < 0.05$  vs. the H/R group, and  $\Delta P < 0.05$  vs. the H/R+CIN PMNs EXOs group.

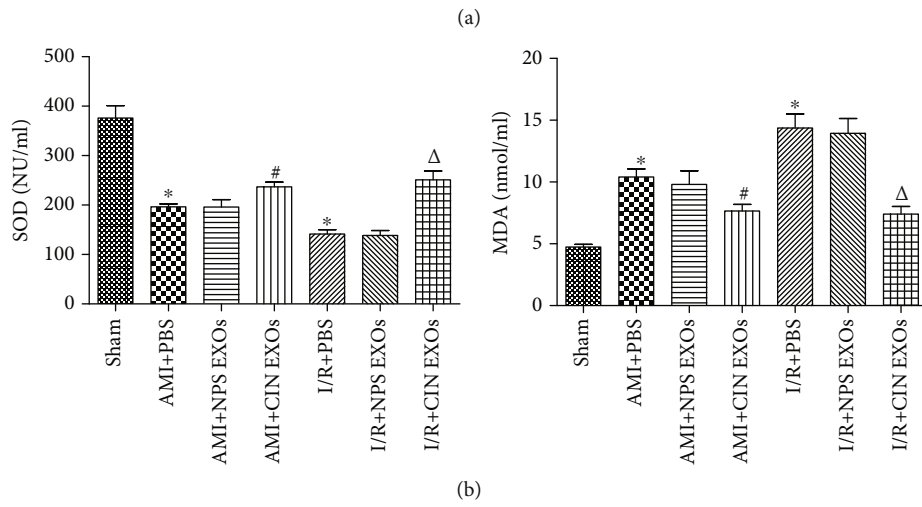
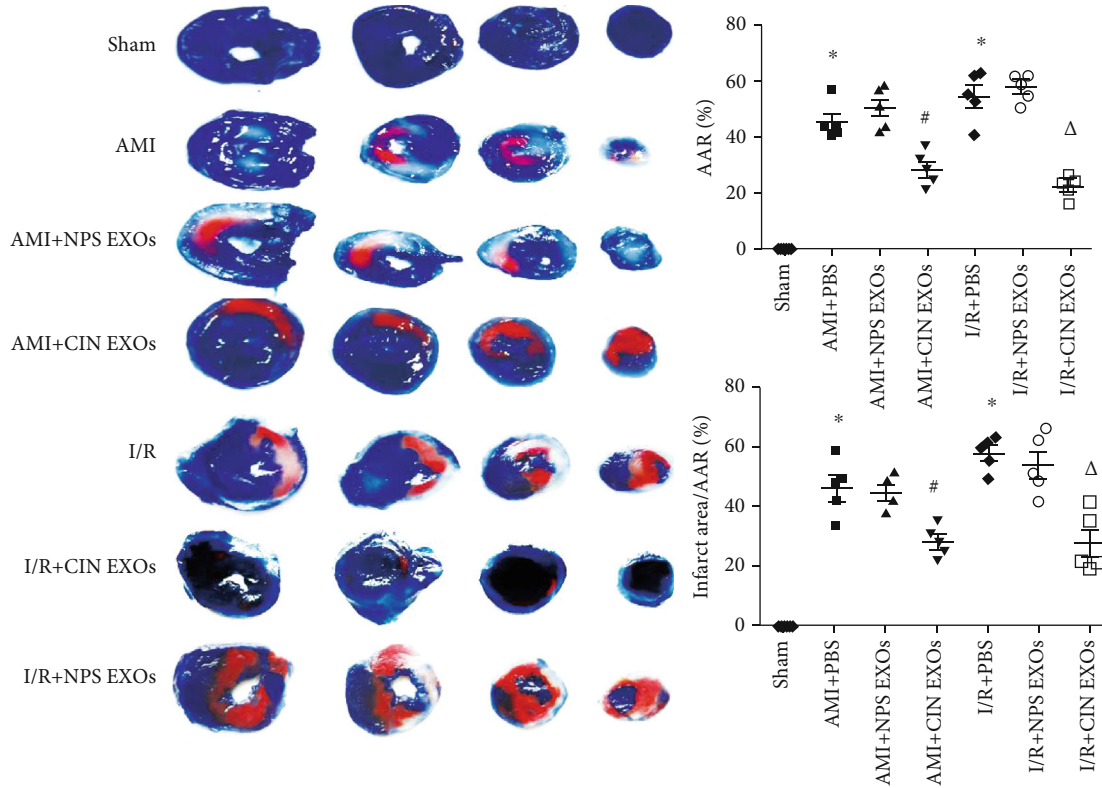


FIGURE 9: Continued.

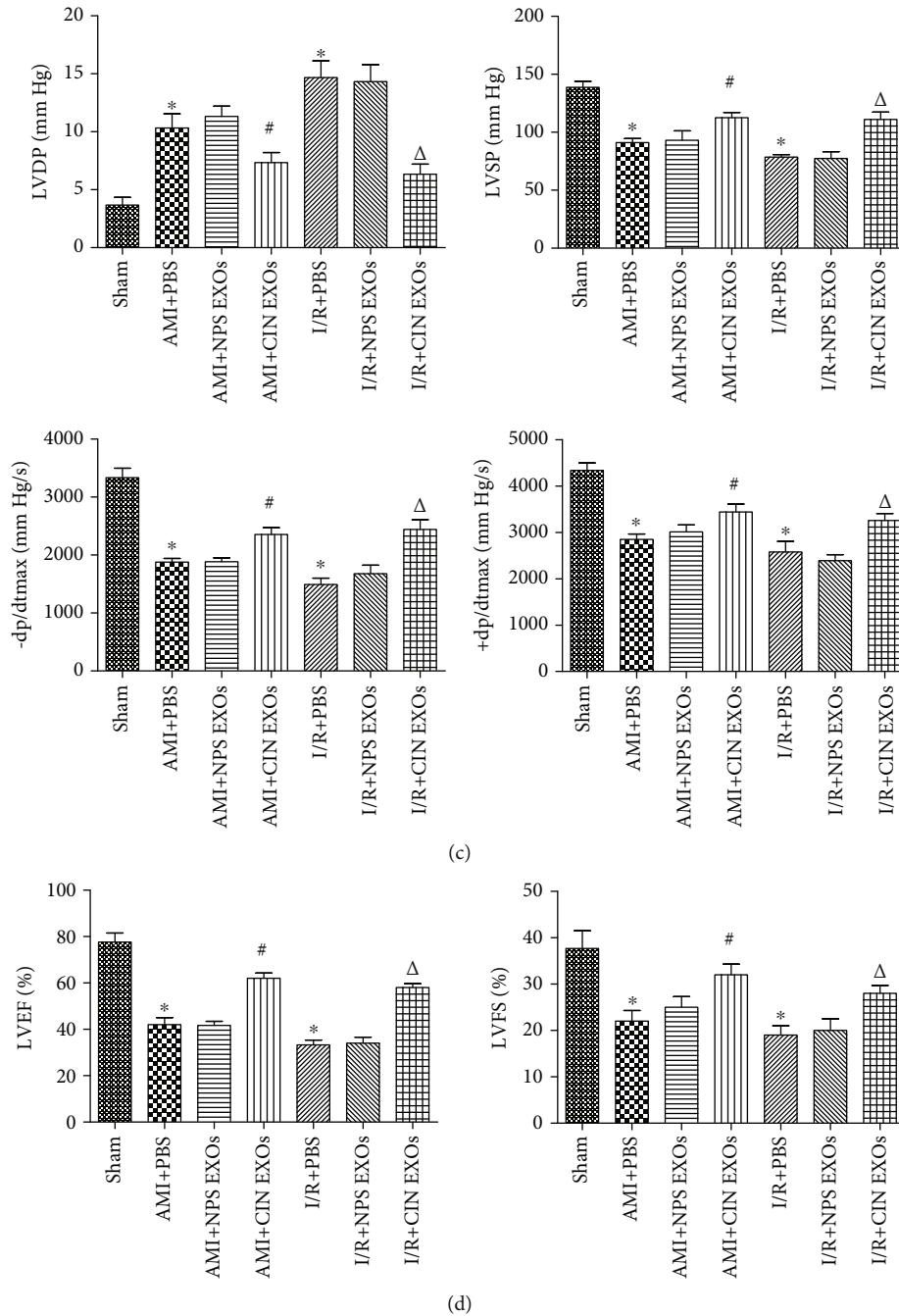


FIGURE 9: CaSR-stimulated PMNs protect the myocardium. (a) Different layers of myocardial tissue under various treatments. The Evans blue-stained portion (area not at risk; ANAR), the unstained portion (area at risk; AAR), the ischaemic area (red), and the infarct area (white) are expressed as a % of the AAR. (b) Rat peripheral blood was extracted, and the SOD and MDA contents were detected. (c) Comparison of the LVSP, LVDP, + dp/dtmax, -dp/dtmax of rats from different groups. (d) Effect of exosomes on cardiac function by echocardiographic assessment. Data are shown as the means  $\pm$  SD; \* $P$  < 0.05 vs. the sham group, # $P$  < 0.05 vs. the AMI group and,  $\Delta P$  < 0.05 vs. the I/R group. Data are representative of three independent experiments.

Much evidence has shown that exosomes have great potential in tissue regeneration and injury repair [30]. The exosomes released by mesenchymal stem cells transport miR-21a-5p into the myocardium, downregulating the expression of proapoptotic proteins such as Peli1 and FasL and thus inducing myocardium protection and repair [31]. PMNs can also secrete exosomes, and circulating exosomes

contain Annexin A1 and anti-inflammatory proteins to inhibit the adhesion of PMNs to endothelial cells and the inflammatory recruitment of PMNs [32]. Therefore, we want to know whether the effects of PMNs on cardiomyocytes are also associated with exosomes.

In our research, the vesicles isolated from the supernatant of the PMNs culture were identified as exosomes. Subsequently,



we observed that exosomes secreted by PMNs were taken up by cardiomyocytes. In subsequent experiments, exosomes secreted by cinacalcet-activated PMNs increased the expression of p-AKT and Bcl-xl, reduced the expression of Bax and Nox2, and reduced the apoptosis rate of the cardiomyocytes. All these results showed that PMNs-derived exosomes stimulated by CaSR can significantly inhibit cardiomyocytes H/R injury. In addition, these results were reversed by treatment with the AKT signaling pathway inhibitor HY15186. Therefore, we also speculated that CaSR-stimulated PMN-derived exosomes play a role in cardiomyocytes related to the AKT signaling pathway.

According to the Tasaralgil et al., the levels of p-AKT/AKT are significantly reduced after myocardial infarction; however, the apoptosis and necrosis of cardiomyocytes are reduced after increasing the activity of p-AKT [33]. Activation of the AKT signaling pathway has also been shown to reduce the accumulation of ROS induced by I/R in cardiomyocytes to protect the myocardium [34]. This finding is consistent with our findings that the AKT signaling pathway in cardiomyocytes was activated after coculturing with CaSR-stimulated PMNs. Furthermore, Nox2 expression and ROS production were attenuated, thereby, significantly attenuating H/R-induced cardiomyocyte apoptosis.

Subsequently, the main components in exosomes were identified. We found that there were 1303 upregulated lncRNAs in the exosomes secreted by CaSR-stimulated PMNs compared with the exosomes secreted by unstimulated PMNs through high-throughput sequencing technology. We selected lncRNA 39868 for further study because of its high expression. Moreover, the Gene Ontology analysis predicted that the PDGFD protein was the target of lncRNA 39868.

We determined that PDGFD was significantly decreased in the myocardium after AMI or I/R, which suggests that PDGFD is associated with myocardial injury. PDGFD is highly expressed in the myocardium and arterial vascular smooth muscle cells throughout development and adulthood, and high expression of PDGFD induces vascular remodeling, stimulates the proliferation of primary heart fibroblasts in heart-specific transgenic mice, and is involved in the repair process of the infarcted myocardium [35, 36]. It is worth noting that in our subsequent studies, highly expressed PDGFD was related to the apoptosis rate of primary cardiomyocytes after ischaemia-reperfusion injury, suggesting that PDGFD is involved in the repair process of myocardial hypoxia-reoxygenation. In subsequent experiments, exosomes secreted by CaSR-stimulated PMNs increased the expression of PDGFD in cardiomyocytes. These results further strengthen our prediction that PDGFD is the downstream target protein of lncRNA 39868 and is involved in the regulation of cardiomyocyte H/R injury. Moreover, we found that indicators of myocardial injury including PDGFD, Bax, MDA, TNF- $\alpha$ , and cardiomyocyte apoptosis were attenuated after cardiomyocytes were cocultured with CaSR-stimulated PMN-derived exosomes; however, silencing lncRNA 39868 reversed these changes.

In vivo, when exosomes extracted from CaSR-stimulated PMNs were injected into rats with ischaemia-reperfusion, we

found that infarcted myocardium was significantly reduced, the content of SOD in the serum was increased, the content of MDA was decreased, and the cardiac function was improved. These results indicate that CaSR-activated PMN-derived exosomes can reduce the myocardium I/R injury. In addition, we found that exosomes extracted from NPS-2143-exposed PMNs enhanced the damage of cardiomyocytes induced by hypoxia-reoxygenation in vitro. However, the results among the different groups were not statistically significant in vivo. We suspect that other cells or substances must be involved in this process.

## 5. Conclusions

In summary, exosomes secreted by CaSR-activated PMNs are taken up by cardiomyocytes to enhance the expression of PDGFD, which is regulated by lncRNA 39868 through the AKT pathway, thereby, attenuating myocardial ischaemia-reperfusion injury. This research may provide guidance for the clinical therapy of acute myocardial infarction.

## Data Availability

The data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare no conflict of interest.

## Acknowledgments

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## Supplementary Materials

Protein expression and SOD and MDA detection in AMI and I/R models. Next, we tested the expression of Bcl-2 and Bax in myocardial tissue when AMI and I/R occurred. The results showed that the expression of Bax increased and Bcl-2 expression decreased. In addition, the ratio of Bcl-2 to Bax decreased much more significantly after AMI and I/R (Figure A). We also detected that the concentration of superoxide dismutase (SOD) decreased and the secretion of malondialdehyde (MDA) increased in serum after AMI and I/R (Figure B). (*Supplementary materials*)

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