

Berberine Upregulates P-Glycoprotein in Human Caco-2 Cells and in an Experimental Model of Colitis in the Rat via Activation of Nrf2-Dependent Mechanisms^S

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ABSTRACT

Downregulation of P-glycoprotein (P-gp) is implicated in the pathophysiology of inflammatory bowel disease (IBD). Berberine, a principal isoquinoline alkaloid extracted from *Berberis* species, has been reported to exhibit therapeutic potential in IBD. In this study, we used a dextran sulfate sodium (DSS)-induced colitis rat model to evaluate the effect of berberine on P-gp and explore its mechanism of action. Berberine treatment improved DSS-induced colitis symptoms, attenuated inflammatory markers (myeloperoxidase, tumor necrosis factor- α , and interleukin-1 β and -6), and enhanced P-gp expression in a dose-dependent manner. Although colonic expression of the P-gp-related nuclear receptor pregnane X receptor and transcription factor nuclear factor erythroid 2-related factor 2 (Nrf2) were downregulated in the colitis model, gene and protein expression analysis revealed

that berberine treatment reversed only the downregulation of Nrf2. In vitro studies using Caco-2 cells showed that the multidrug resistance 1 (*MDR1*) gene and P-gp protein were upregulated by berberine in a dose- and time-dependent manner. Significant upregulation of the *MDR1* gene by berberine was abrogated by Nrf2 silencing, indicating that the Nrf2-mediated pathway was responsible for this activation. Luciferase assays showed a dose-dependent increase in Nrf2 reporter gene activity after berberine treatment in Caco-2 cells, with a significant 2-fold elevation at 2.5 μ M berberine, suggesting that berberine is a strong Nrf2 activator. These results indicate the possible involvement of Nrf2-mediated upregulation of P-gp in the therapeutic effect of berberine on colitis and highlight the potential of P-gp and/or Nrf2 as new therapeutic targets for IBD.

Introduction

Inflammatory bowel disease (IBD) is a chronic inflammatory disorder that affects the gastrointestinal tract, and its incidence and clinical severity have grown worldwide. IBD comprises two different diseases: ulcerative colitis (UC) and Crohn disease. Symptoms include diarrhea, abdominal pain, body weight loss, rectal bleeding, malnutrition, and fever (Zhang et al., 2015a). Currently, the exact causes of IBD are poorly understood; however, impaired barrier function of the gut epithelium is reported to be an important factor in IBD pathogenesis (Miner-Williams and Moughan, 2016; Tili et al., 2017).

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P-glycoprotein (P-gp), encoded by the multidrug resistance 1 gene (*MDR1* in humans and homologs *mdr1a* and *mdr1b* in rodents), is one of the most important components of the intestinal barrier (Huls et al., 2009). As an ATP-dependent efflux transporter, P-gp transports numerous lipophilic cationic drugs and other harmful molecules out of the intestinal mucosa (Sharom, 2011). Additionally, P-gp transports cytokines, such as interferon- γ , interleukin (IL)-1 β , and IL-4, from activated normal lymphocytes to the surrounding fluid, and this could regulate a series of physiologic processes (Johnstone et al., 2000). Growing evidence indicates that alterations in P-gp expression and function may contribute to IBD development and persistence (Banner et al., 2004; Blokzijl et al., 2007; Gutmann et al., 2008). Decreased P-gp expression has been reported in the intestinal mucosa of UC patients (Blokzijl et al., 2007). Moreover, an animal study reported that mice deficient in *mdr1a* spontaneously developed colitis resembling human UC (Banner et al., 2004), whereas mice deficient for other transporters, such as MRP2 and BCRP, did not

ABBREVIATIONS: BBB, berberine; DAI, disease activity index; DSS, dextran sulfate sodium; ELISA, enzyme-linked immunosorbent assay; GAPDH, glyceraldehyde 3-phosphate dehydrogenase; IBD, inflammatory bowel disease; IL, interleukin; Keap1, Kelch-like ECH-associated protein 1; MDR1, multidrug resistance 1; MPO, myeloperoxidase; Nrf2, nuclear factor erythroid 2-related factor 2; P-gp, P-glycoprotein; PXR, pregnane X receptor; qRT-PCR, quantitative real-time polymerase chain reaction; rho123, rhodamine 123; SFN, sulforaphane; siRNA, small interfering RNA; TNF, tumor necrosis factor; UC, ulcerative colitis.

(Chu et al., 2006). In addition, several studies characterizing the association between *MDR1* polymorphisms and IBD susceptibility (Brinar et al., 2013; Zhao et al., 2015) have indicated that stimulating P-gp expression and function could be a new treatment of IBD.

The nuclear receptor pregnane X receptor (PXR) plays a major role in activating P-gp expression (Sehirli et al., 2015). Although PXR dysregulation in the intestine likely contributes to UC pathophysiology (Cheng et al., 2010), PXR activation has been demonstrated to be an effective treatment in an experimental colitis mouse model and in human cell lines (Zhang et al., 2015a,b). Nuclear factor erythroid 2-related factor 2 (Nrf2), a cytoprotective transcription factor against oxidative stress, plays an important role in the antioxidant response by regulating the transcription of several detoxifying/antioxidant enzymes and transporters, including P-gp (Aleksunes and Klaassen, 2012). Nrf2^{-/-} mice exhibit increased sensitivity to dextran sulfate sodium (DSS)-mediated colitis (Khor et al., 2006), and activation of Nrf2 by its inducer sulforaphane (SFN) increases P-gp expression and function at the rat blood-brain barrier (Wang et al., 2014). These reports suggest that Nrf2 may mediate P-gp dysregulation in the intestinal barrier in colitis.

Berberine is the major isoquinoline alkaloid in the stems and roots of *Berberis* species. Several studies have reported the therapeutic potential of berberine for IBD (Hong et al., 2012; Yan et al., 2012; Li et al., 2016; Liu et al., 2018). Among the numerous possible mechanisms involved in the efficacy of berberine in IBD (Habtemariam, 2016), recent reports have focused on berberine-mediated improvements in gut epithelial barrier dysfunction and the role of tight junction proteins zona occludens-1 and occludin (Gu et al., 2009; Yan et al., 2012; Tan et al., 2015; Li et al., 2016). Numerous reports have demonstrated that berberine is a P-gp substrate and that it regulates P-gp expression and function (Lin et al., 1999b; Shitan et al., 2007; Qiu et al., 2009; Zhang et al., 2011; Shan et al., 2013). Most of these studies were performed in vitro, however, and some were also controversial. Whether berberine improves the intestinal barrier by regulating P-gp expression in a DSS-induced colitis rat model has yet to be determined. Another question is whether and how the colitis-related nuclear receptor PXR and nuclear factor Nrf2 contribute to gut barrier healing if berberine exhibits a regulatory effect on P-gp.

Therefore, in the current study, the effect of berberine on P-gp expression in the colon was assessed in a DSS-induced colitis rat model. For further mechanistic investigation, the regulation of P-gp expression and activity in Caco-2 cells, a human epithelial colorectal adenocarcinoma cell line that naturally expresses the *MDR1* gene, in response to berberine treatment were also characterized.

Materials and Methods

Chemicals and Reagents. Berberine hydrochloride was obtained from Shanghai Boyun Biotech Co. (Shanghai, China) at the highest available purity (≥95%). DSS (mol. wt. 36,000–50,000) was purchased from MP Biomedicals (Santa Ana, CA). Nrf2 small interfering RNA (siRNA) and control siRNA were obtained from Invitrogen Life Technologies (Shanghai, China). Dulbecco's modified Eagle's medium, fetal bovine serum, streptomycin, Triton X-100, and TRIzol reagent were purchased from Sigma-Aldrich (St. Louis, MO).

Animal Care and Experimental Design. Male Sprague-Dawley rats (~250 g) were obtained from the Experimental Animal Center of Xi'an Jiaotong University (Xi'an, China) [license no. SCXK (Shaanxi) 2012-003]. Animals were housed in a climate-controlled vivarium with a relative humidity of 55% ± 5% under 12-hour day/night cycles and provided with food and water ad libitum.

Rats were divided into four groups: normal, colitis, colitis + 10 mg/kg berberine (BBR LD), and colitis + 40 mg/kg berberine (BBR HD). Colitis was induced by administration of 5% (w/v) DSS in drinking water for 7 days. Berberine was dissolved in water and administered to the BBR LD and BBR HD groups via oral gavage during those 7 days. In parallel, the same quantity of water was administered to the rats from the control and colitis groups via oral gavage for 7 days. The berberine treatment dosage was determined based on a previous report (Li et al., 2016), and a preliminary experimental result in our laboratory (data not shown). This study was approved by the Ethical Committee of Xi'an Jiaotong University, and studies were performed in accordance with the Guide for the Care and Use of Laboratory Animals of the Ethical Committee of Xi'an Jiaotong University, Xi'an, China (permit no. XJTU 2011-0045).

Daily Observation and Sample Collection. Rats were monitored daily for stool consistency, body weight, and rectal bleeding during the experimental period. Disease activity index (DAI) was measured as described previously in our laboratory (Huang et al., 2015). On the final day, animals were sacrificed under anesthesia, and the colon was immediately obtained to identify ulcers in the colonic mucosa and measure colon length and weight. Additionally, 1 cm of the distal colon was excised for histologic evaluation. The remaining colon was stored in liquid nitrogen for quantitative real-time polymerase chain reaction (qRT-PCR), enzyme-linked immunosorbent assay (ELISA), and Western blot analysis. The spleen was removed to measure its weight, as spleen weight represents an index of systemic inflammation (Antonoli et al., 2007).

Histologic Analysis of Colon Tissues. The colon tissues were removed and fixed with 10% formalin solution overnight. Histologic sections were stained with H&E. Colon injury and inflammation were graded on a 0–5 scale, as described in previous reports (Maeda et al., 2005; Jing et al., 2016).

Evaluation of Myeloperoxidase Activity in Colonic Mucosa. Myeloperoxidase (MPO) activity is used to measure the degree of inflammation in colon tissue (Metzler et al., 2011). Its activity in the colonic mucosa was evaluated as described previously (Huang et al., 2015). One unit of MPO activity indicates the quantity of enzyme required for converting 1 nmol of hydrogen peroxide to water per minute at ~25°C.

Determination of Colonic Cytokines. The levels of IL-1β, IL-6, and tumor necrosis factor (TNF-α) in colon homogenates were determined with ELISA (R&D Systems, Minneapolis, MN) according to the protocol of the manufacturer.

Cell Culture. Caco-2 cells (American Type Culture Collection, Rockville, MD) were cultured in Dulbecco's modified Eagle's medium containing 10% fetal bovine serum, 100 U/ml penicillin, and 100 μg/ml streptomycin. The cell medium was changed with new medium every 2 days. Cells were passaged upon reaching ~80% confluence.

Drug or siRNA Treatment in Caco-2 Cells. Caco-2 cells were plated in six-well plates at a density of 8 × 10⁵ cells/well and incubated at 37°C. After 24 hours, the cells were treated with 0, 0.1, 0.5, and 2.5 μM berberine for 48 hours or with 2.5 μM berberine for 0, 12, 24, or 48 hours. For RNA silencing, we used HiPerFect transfection reagent (Qiagen, Hilden, Germany) to transfect Caco-2 cells with 100 nM siRNA targeting human *Nrf2* (Hs_NRF2L2_7) or negative control siRNA (Allstar Negative Control siRNA; Qiagen), followed by incubation for 72 hours. During the final 48 hours, 2.5 μM berberine was added to the culture medium. Cells were then rinsed, scraped, and used for Western blotting or qRT-PCR analysis.

Uptake of Rhodamine 123 in Caco-2 Cells. Uptake of rhodamine 123 (rho123) in Caco-2 cells was measured for the evaluation of P-gp activity (Zhang et al., 2011). After pretreatment with berberine at

0, 0.1, 0.5, or 2.5 μM for 48 hours or with 2.5 μM berberine for 0, 12, 24, or 48 hours. Caco-2 cells were washed with Hank's balanced salt solution (Biochrom, Berlin, Germany) and treated with 5 μM rho123 for 120 minutes. At the end of the experiment, cells were washed again and lysed with Triton X-100. Cell lysate (150 μl) was transferred to a black 96-well microplate (BD Biosciences, Franklin Lakes, NJ), and the fluorescence intensity of rho123 was determined (excitation wavelength: 485 nm; emission wavelength: 538 nm) using a WALLAC multilabel/luminescence counter (PerkinElmer, Waltham, MA).

qRT-PCR. Total RNA was extracted from colon tissues and Caco-2 cells using TRIzol reagent according to the protocols of the manufacturer. RNA concentrations were calculated by spectrophotometer at 260 nm. Total RNA (5 μg) was reverse-transcribed into single-stranded cDNA using the Superscript III First-Strand Synthesis System (Invitrogen, Carlsbad, CA) for RT-PCR. The cDNA samples were subjected to qPCR with SYBR Green in an ABI 7500 RT-PCR system (Applied Biosystems, Foster City, CA). The primers for mRNA quantification are shown in Supplemental Table 1. Reactions involved the following protocol: 95°C for 5 minutes, followed by 40 cycles of 95°C for 15 seconds and 60°C for 1 minute. The mRNA levels were calculated by the $\Delta\Delta\text{C}_\text{T}$ method, and data were normalized to levels of glyceraldehyde 3-phosphate dehydrogenase (*GAPDH*).

Western Blotting Analysis. Cytoplasmic and nuclear extracts of colon tissues and cells were prepared as described in our previous reports (Jing et al., 2016). Proteins of interest in the cytoplasmic and nuclear fractions of colon tissues or cells were measured by Western blotting as described in our previous report (Jing et al., 2016, 2017) using the following antibodies: anti-P-gp (1:400, cat. no. 517310; Calbiochem, San Diego, CA), anti-PXR (1:1000, cat. no. ab118336; Abcam, Cambridge, MA), anti-Kelch-like ECH-associated protein 1 (Keap1; 1:1000, cat. no. ab139729; Abcam), and anti-Nrf2 (1:1000, cat. no. ab89443; Abcam). Mouse antibodies against histone H3 (1:10,000, cat. no. ab32356; Abcam) and *GAPDH* (1:10,000, cat. no. ab8245; Abcam) were used to measure nuclear and cytosolic housekeeping proteins, respectively.

Luciferase Assay. Caco-2 cells were plated in 96-well plates at a density of 5×10^4 cells/well and incubated at 37°C. After 24 hours, the cells were transfected with pGL3-ARE-Luc, pEF-Nrf2, and pRL-TK (Promega, Madison, WI) using LipofectAMINE 2000 (Invitrogen) according to the protocols of the manufacturer. After transfection, Caco-2 cells were treated with SFN (10 μM) or berberine (0.1, 0.5, or 2.5 μM) for 24 hours, and then cell lysates were prepared. Luciferase activity was measured using a SpectraMax M5 multi-mode microplate reader (Molecular Devices, San Jose, CA). Firefly luciferase activity was normalized to that of *Renilla* luciferase, and activity was expressed as fold induction relative to blank control.

Data Analysis. Data are presented as the mean \pm S.E.M. All statistical evaluations were performed using GraphPad Prism 6.0 software (GraphPad, San Diego, CA) with unpaired Student's *t* test or one-way analysis of variance. A value of $P < 0.05$ was considered statistically significant.

Results

Berberine Alleviated DSS-Induced Colitis. A colitis rat model was successfully developed using 5% DSS, resulting in severe colitis-like symptoms. The DAI, including stool consistency, body weight loss, and gross bleeding, was elevated after DSS administration for 2 days (Fig. 1A), in agreement with our previous study (Jing et al., 2016). Rats with DSS-induced colitis treated with berberine (10 and 40 mg/kg) for 7 days showed reduced responses to DSS and lowering of DAI scores (Fig. 1A). An increase in the weight-length ratio of the colon in a colitis rat model is a major biologic marker for colonic inflammation (Martin et al., 2016). In the current study, rats with DSS-induced colitis showed an increased colon weight-length ratio after DSS administration

for 1 week, whereas berberine treatment (10 and 40 mg/kg) reversed this trend (Fig. 1D). Splenomegaly is common among patients with UC (Ashrafi et al., 2014), and spleen weight represents an index of systemic inflammation (Antonioni et al., 2007). In agreement with earlier studies (Jing et al., 2016), enlarged spleens were observed in DSS-treated rats, and this was significantly attenuated by berberine (10 and 40 mg/kg) treatment (Fig. 1, B and C). Inflammation of the colonic mucosa in UC is characterized mainly by neutrophil accumulation, which is quantified by measuring MPO activity. We observed increased MPO activity in the colonic mucosa from DSS-treated rats, and we found that berberine administration significantly attenuated this DSS-triggered MPO activation (Fig. 1E). Additionally, histologic studies of the distal colon tissues demonstrated that the severity and extent of inflammatory lesions in the colons of DSS-treated rats were significantly greater than those observed in normal rats; moreover, treatment with 40 mg/kg berberine markedly reduced the histology scores in the colitis group (Supplemental Fig. S1).

Berberine Relieved DSS-Induced Inflammation in the Colon. After DSS administration for 7 days, we measured the concentrations of IL-1 β , IL-6, and TNF- α in colon tissue. The results shown in Fig. 2 indicate that levels of these pro-inflammatory cytokines were much higher in DSS-treated rats than in the normal group. Increases in inflammatory cytokine levels in the DSS-treated rats were significantly attenuated by berberine administration.

Berberine Altered P-gp and Nrf2 Expression in Colons from Rats With DSS-Induced Colitis. The colonic gene expression of *mdr1a* was analyzed by qRT-PCR. Figure 3 shows that DSS administration markedly decreased the expression of *mdr1a* mRNA. In comparison, berberine treatment reversed this reduction in *mdr1a* in the DSS-treated group, inducing levels that were higher than normal. To characterize further the mechanism of action of berberine on *mdr1a* expression, we determined the mRNA expression of nuclear receptor *PXR* and transcription factor *Nrf2*, which are related to colitis. As shown in Fig. 3, both *PXR* and *Nrf2* mRNA levels were significantly decreased in response to DSS administration. Berberine treatment, however, restored only the *Nrf2* mRNA level and had no effect on *PXR* mRNA expression. These results indicate that *Nrf2*, but not *PXR*, may play a critical role in berberine-mediated P-gp induction in the DSS-induced colitis model.

To confirm the preceding results regarding berberine-induced upregulation of *mdr1a* and *Nrf2* gene expression, we evaluated the protein expression of P-gp, PXR, and Nrf2 using Western blotting. Compared with those in normal rats, the protein expression of P-gp, PXR, and nuclear Nrf2 was decreased in DSS-treated rats. Berberine administration significantly reversed the downregulation of P-gp and nuclear Nrf2 in the DSS-treated group (Fig. 4); however, consistent with the results of the mRNA expression experiment, berberine exhibited no effect on PXR protein expression. Taken together, our results suggest that berberine upregulates the mRNA and protein levels of P-gp, possibly via Nrf2 activation.

Berberine Upregulated P-gp in a Dose- and Time-Dependent Manner. To characterize the mechanism of P-gp upregulation by berberine in vitro, Caco-2 cells were incubated with berberine (0, 0.1, 0.5, or 2.5 μM) for 48 hours. Results in Fig. 5, A and B show that the expression of *MDR1* gene and P-gp protein was significantly upregulated by berberine treatment

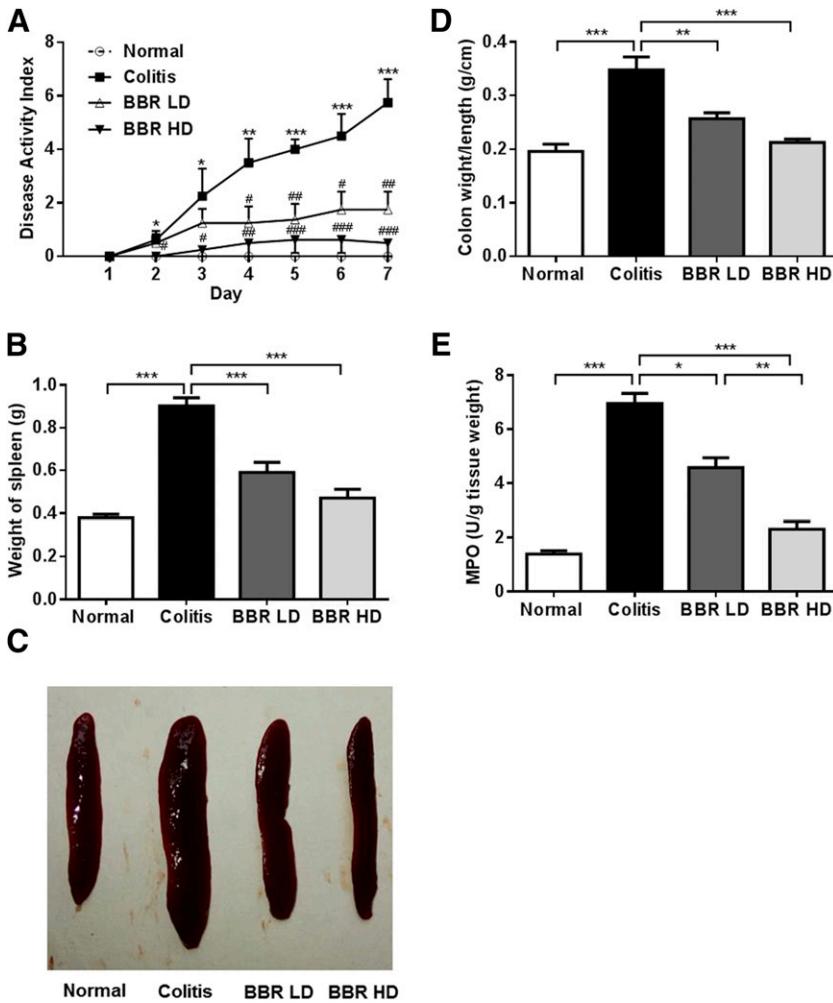


Fig. 1. Berberine improved colitis-like symptoms in DSS-induced colitis rats. (A) DAI, (B and C) spleen weight, (D) colon weight-length ratio, and (E) MPO activity in colon. Data represent the mean \pm S.E.M. ($n = 8$ rats per group). * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$. BBR, berberine; HD, high dose; LD, low dose.

at concentrations of 0.5 and 2.5 μ M. P-gp function was evaluated by assessing the uptake of rho123, a P-gp substrate. After berberine treatment (0.1, 0.5, or 2.5 μ M), intracellular uptake of rho123 was significantly decreased (Fig. 5C), indicating an increase in P-gp function in response to berberine treatment. Furthermore, we evaluated P-gp regulation in Caco-2 cells by incubating them with 2.5 μ M berberine for 0, 12, 24, or 48 hours. Results showed that, in addition to inducing dose-dependent effects, berberine treatment increased *MDR1* gene expression and P-gp protein expression and function in a time-dependent manner (Fig. 5, D–F).

Berberine Induced P-gp Expression and Function Via Nrf2 in Caco-2 Cells. To investigate further whether activation of Nrf2 is necessary for berberine-mediated P-gp upregulation, an *Nrf2* gene-silencing experiment was conducted in Caco-2 cells. The results in Fig. 6A show that Nrf2 expression was decreased by $\sim 70\%$ after transfection with *Nrf2*-siRNA. qRT-PCR was used to analyze changes in *MDR1* gene expression. Figure 6B shows that *Nrf2* silencing significantly reduced *MDR1* mRNA expression to 54% that in the negative control; moreover, activation of *MDR1* by berberine was abolished by *Nrf2* silencing (Fig. 6B). These results demonstrate that berberine induces *MDR1* gene expression via Nrf2 activation in Caco-2 cells.

Effects of Berberine on Nrf2 Activation in Caco-2 Cells. Although the effect of berberine on the mRNA expression of *Nrf2* was investigated in vivo, it may not accurately

represent the effect of berberine on *Nrf2* gene function. Therefore, the effect of berberine on Nrf2 activation was determined using a luciferase reporter assay in Caco-2 cells, which were transiently transfected with reporter plasmids. As shown in Fig. 6C, Nrf2 reporter gene activity in the SFN group increased significantly to a level 2.5-fold of that in the control group; similarly, berberine increased Nrf2 reporter gene activity in a dose-dependent manner, with a significant 2-fold elevation at 2.5 μ M berberine. To confirm the regulatory effect of berberine on the nuclear translocation of Nrf2, we also measured the abundance of the Nrf2 inhibitor Keap1 in the cytoplasm and Nrf2 expression in the nucleus of Caco-2 cells in response to berberine (2.5 μ M) and SFN treatment. Treatment with the Nrf2 activator SFN significantly reduced cytoplasmic Keap1 abundance and significantly increased the nuclear translocation of Nrf2; similar results were observed after treatment with berberine (Fig. 6, D and E). These data demonstrate the role of berberine as a strong Nrf2 activator.

Discussion

Rats with DSS-induced colitis showed symptoms similar to those associated with UC patients, including diarrhea, body weight loss, bloody stool, and mucosal ulceration, and this model is used extensively for basic research and drug

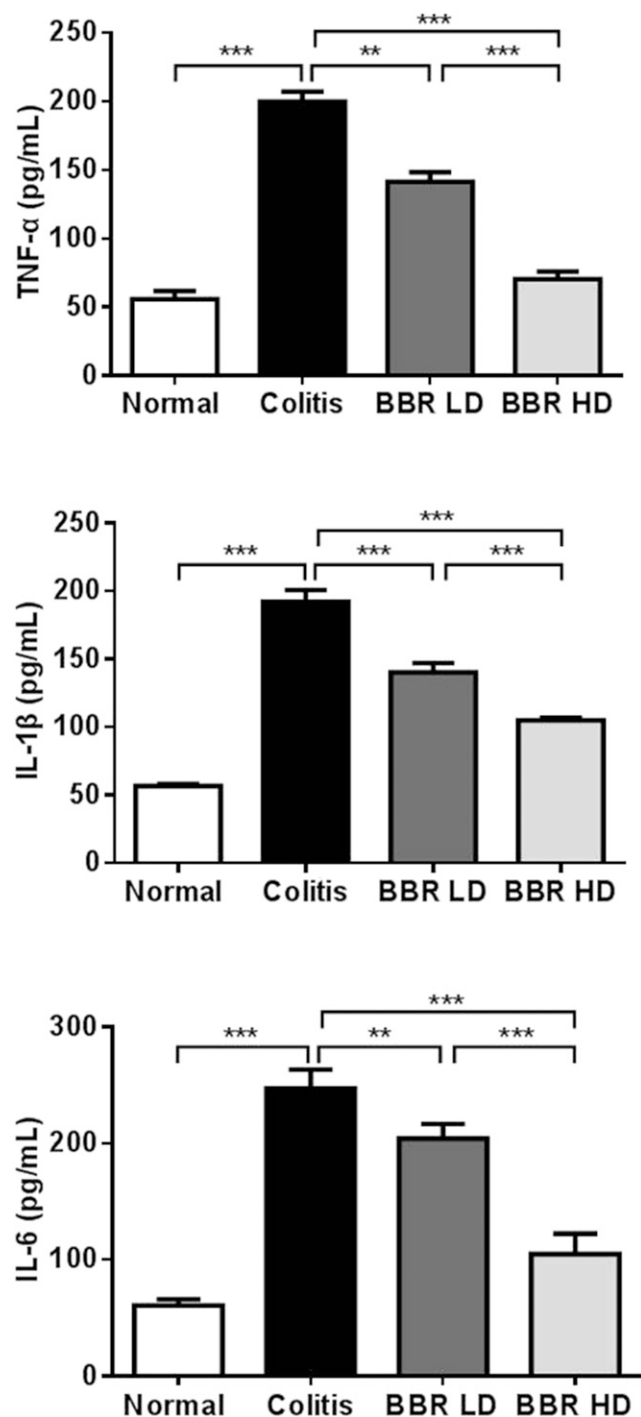


Fig. 2. Berberine relieved DSS-induced inflammation in colon tissues. Protein concentrations of the inflammation-related cytokines TNF- α , IL-1 β , and IL-6 in colonic homogenates were determined by ELISA. Data represent the mean \pm S.E.M. ($n = 8$ rats per group). ** $P < 0.01$; *** $P < 0.001$. HD, high dose; LD, low dose.

discovery. In this study, using the DSS-induced colitis model, we observed neutrophil infiltration in colon tissues, as evidenced by increased MPO activity in the colonic mucosa, as well as splenomegaly, which is commonly reported in human UC (Ashrafi et al., 2014; Peterson et al., 2016) (Fig. 1). After DSS administration, we also observed increased levels of pro-inflammatory cytokines in colon tissues (TNF- α , IL-1 β , and IL-6). These findings are similar to those of our previous study

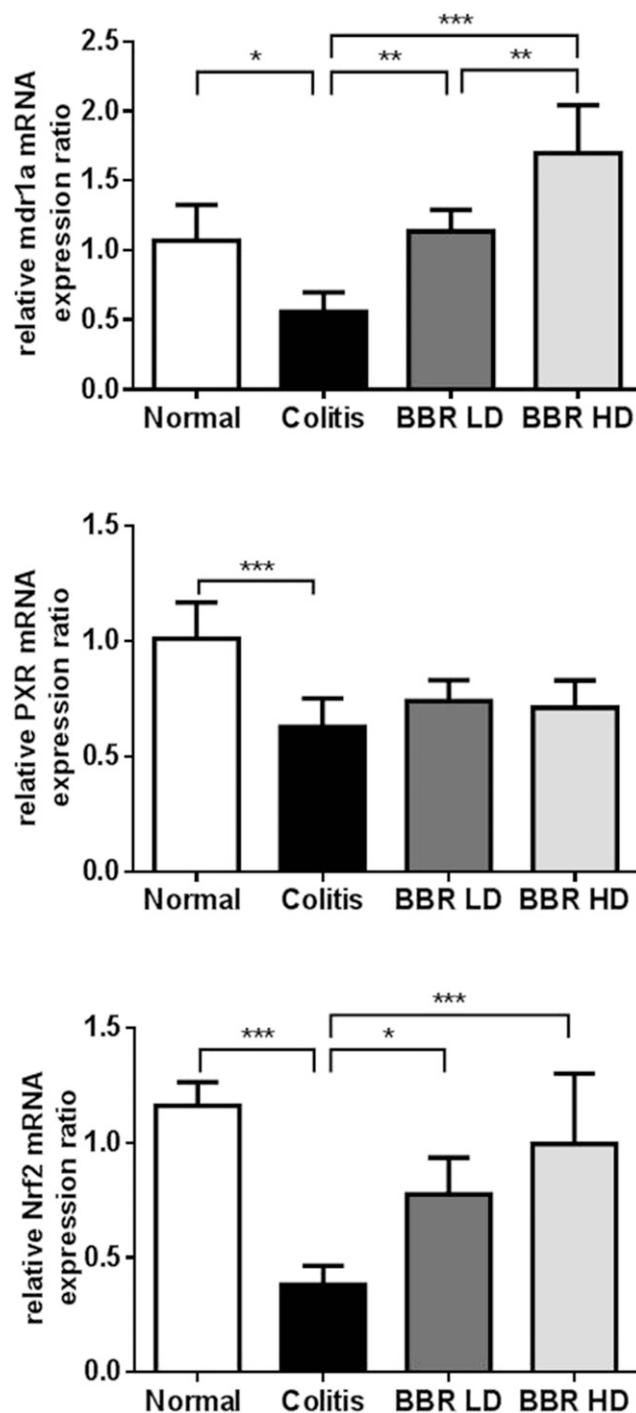


Fig. 3. Berberine regulated the expression of *mdr1a* and *Nrf2* and had no effect on *PXR* expression in DSS-induced colitis rats. qRT-PCR was performed to measure the gene expression of *mdr1a*, *PXR*, and *Nrf2*. Data represent the mean \pm S.E.M. ($n = 8$ rats per group). * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$. HD, high dose; LD, low dose.

involving rats with colitis induced by 5% DSS administration (Jing et al., 2016). In this study, berberine treatment alleviated colitis symptoms in a dose-dependent manner (Figs. 1 and 2). Although similar results have been reported previously (Zhou and Mineshita, 2000; Lee et al., 2010; Hong et al., 2012; Yan et al., 2012; Li et al., 2016), these studies used different colitis models and different rodents. This is the first report showing an improvement in DSS-induced colitis

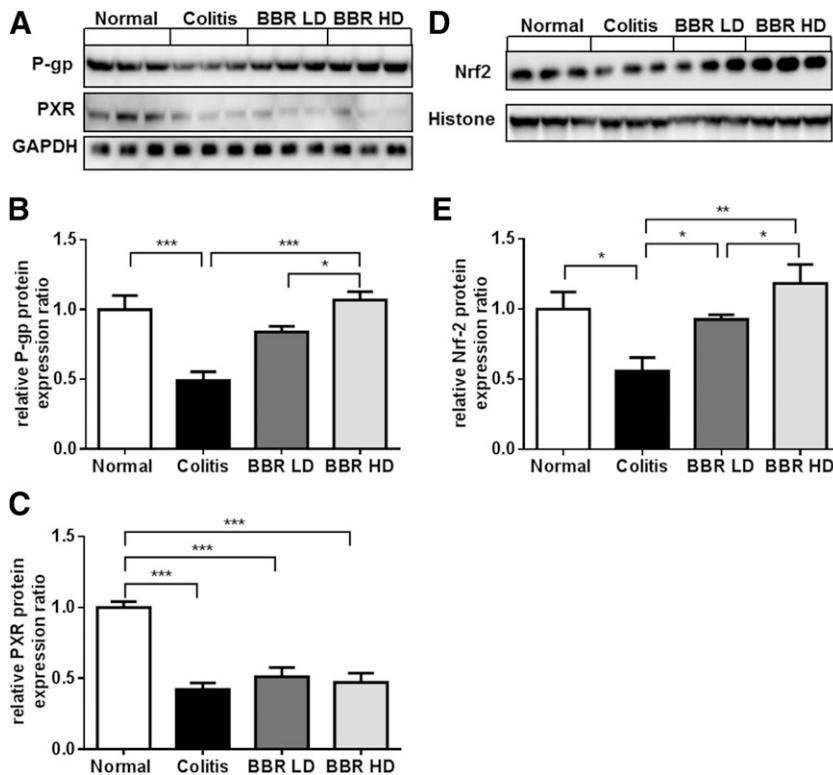


Fig. 4. Berberine increased P-gp and Nrf2 expression in DSS-induced colitis rats. (A and D) Representative Western blots and (B, C, and E) group data depicting P-gp, PXR, and nuclear Nrf2 expression in colon tissues from normal rats, colitis rats, and colitis rats treated with a low dose (LD, 10 mg/kg) or high dose (HD, 40 mg/kg) of berberine. Data represent the mean \pm S.E. M. ($n = 8$ rats per group). * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$. Histone H3 was used as a loading control for nuclear extracts, and GAPDH was used as a loading control for cytoplasmic extracts.

symptoms in rats after berberine administration. The present study not only confirmed the beneficial effects of berberine on DSS-induced colitis in a rat model but also characterized the Nrf2-mediated mechanisms of P-gp upregulation through which berberine improved DSS-induced colitis.

Decreased P-gp expression and activity are implicated in IBD pathogenesis (Englund et al., 2007), and *MDR1* has been shown to be a target gene for IBD therapy (Banner et al., 2004; Sehirli et al., 2015; Jing et al., 2016). Previous studies of an *mdr1a*-deficient colitis model demonstrated that *mdr1a*^{-/-} mice spontaneously developed colonic inflammation that was histologically similar to that observed in human IBD (Panwala et al., 1998; Banner et al., 2004). Additionally, increased P-gp expression and/or function exhibited beneficial effects on colitis symptoms (Saksena et al., 2011; Jing et al., 2016). In agreement with earlier studies using different models, including DSS-induced mouse/rat colitis and trinitro-benzene-sulfonic acid-induced rat colitis (Iizasa et al., 2003; Sehirli et al., 2015; Jing et al., 2016), we observed decreased levels of *mdr1a* mRNA and P-gp protein in the colonic tissues of the colitis rat model in the present study. Berberine treatment abrogated P-gp downregulation at both the mRNA and protein levels in DSS-induced colitis rats (Figs. 3 and 4), indicating that improvements in the intestinal barrier (via P-gp upregulation) contributed to the observed therapeutic effects of berberine on colitis. Berberine-induced P-gp upregulation was also reported in a previous study, in which berberine treatment of 24-hour upregulated P-gp expression and activity in various digestive track cancer cell lines (Lin et al., 1999b). Furthermore, berberine has been reported to upregulate P-gp expression and activity in murine and human hepatoma cells (Lin et al., 1999a). One in vivo study demonstrated that berberine increased the bioavailability of digoxin, a P-gp substrate, through inhibition of

intestinal P-gp (Qiu et al., 2009); however, a biphasic effect of berberine on P-gp ATPase activity was reported in the rat jejunal membrane (Najar et al., 2010). The differences seen in the in vivo and in vitro results may be due to differences in cell strains, dosages, substrates, and durations of exposure. Our findings from this study showing the berberine-mediated upregulation of P-gp expression are in agreement with the findings of most previous studies (Lin et al., 1999a; Qiu et al., 2009; Najar et al., 2010).

The transcriptional regulation of the *MDR1* gene is highly complex. The nuclear receptor PXR and the transcription factor Nrf2 play important roles in elevating *MDR1* gene transcription and ultimately increasing P-gp function (Chen et al., 2012; Jeddi et al., 2018). Additionally, dysregulation of PXR/Nrf2 activity in the intestine is thought to contribute to colitis pathophysiology (Khor et al., 2006; Yang et al., 2017). In the present study of DSS-induced colitis rats, PXR and Nrf2 expression were decreased in the colon, in accordance with previous studies (Hu et al., 2014; Yang et al., 2017); however, in the berberine-treated group, only the decrease in Nrf2 expression was reversed by berberine, with no effect observed on PXR expression (Fig. 4). Although Yu et al. (2011) showed that berberine was an efficacious PXR agonist, their research was based on an in vitro experiment using HepG2 cells.

As a further mechanistic study, P-gp alteration in Caco-2 cells was investigated in response to berberine treatment. Because Caco-2 cells highly express P-gp, this cell line is used extensively for studying P-gp regulatory mechanisms in physiologic and pathologic processes, such as colitis (Saksena et al., 2011, 2013; Jing et al., 2016). Using this in vitro model, we observed that berberine treatment upregulated P-gp expression and function (Fig. 5), a finding in accordance with previous in vitro studies (Shan et al., 2013). The role of Nrf2 in P-gp expression has been investigated in many in vitro and

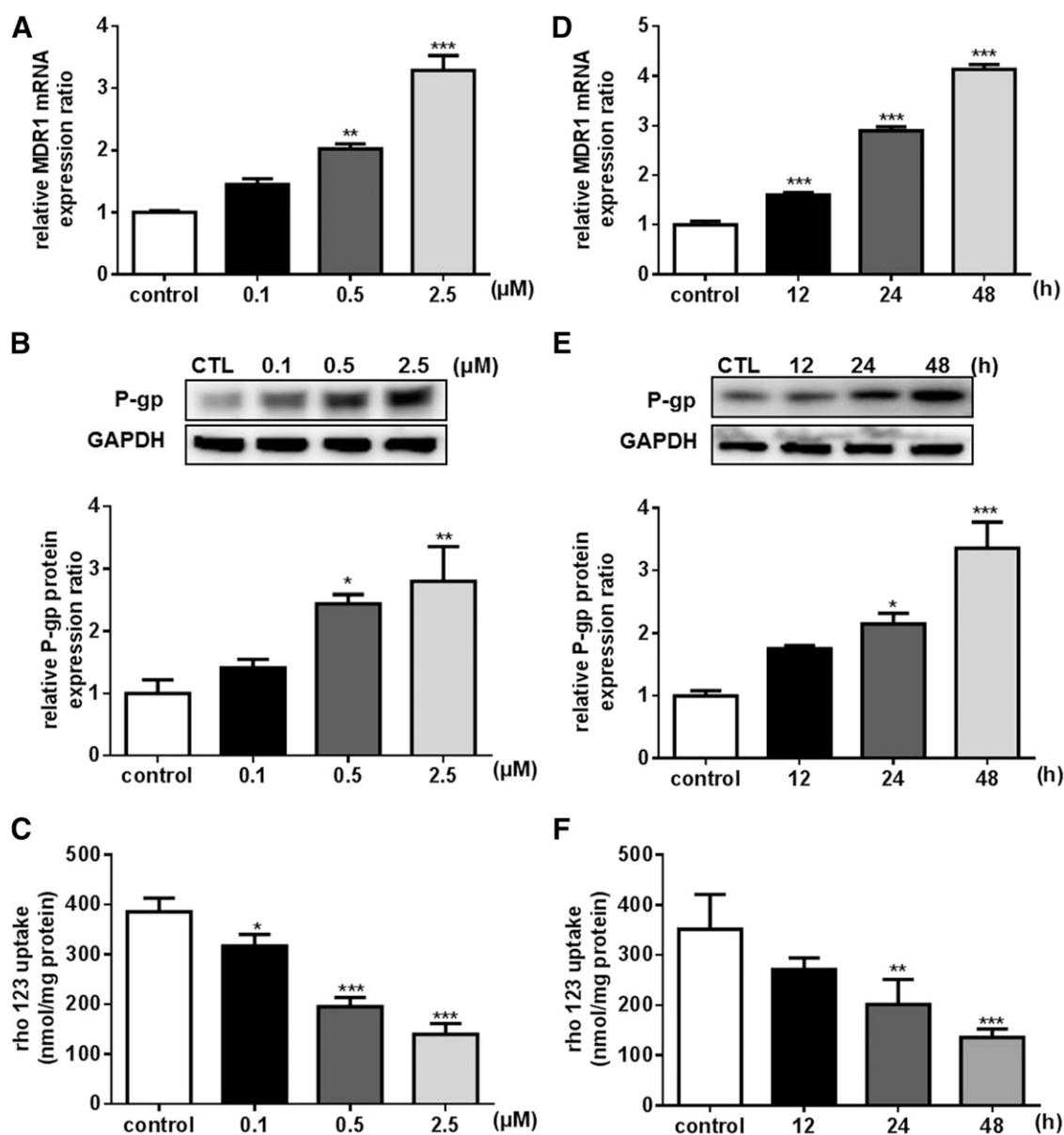


Fig. 5. P-gp was upregulated by berberine treatment in a dose- and time-dependent manner in Caco-2 cells. (A and D) *MDR1* gene expression, (B and E) P-gp protein expression, and (C and F) P-gp function were induced by berberine treatment. qRT-PCR and Western blotting were performed to measure mRNA and protein levels, respectively. Cellular uptake of the P-gp substrate rho123 was used to measure P-gp function. Data represent the mean \pm S.E. M. of six samples from two independent experiments. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ vs. control. GAPDH was used as a loading control for cytoplasmic extracts.

in vivo models (Wang et al., 2014; Jeong et al., 2015). Treatment with the Nrf2 inducer SFN upregulates P-gp protein levels in rat brains (Wang et al., 2014), and the activation of *Nrf2* (through Keap1 knockdown) increases P-gp expression in human renal tubular cells (Jeong et al., 2015). To investigate whether berberine upregulates P-gp through Nrf2 activation, we used Caco-2 cells to perform an *Nrf2* gene silencing experiment. Our data showed that the induction of *MDR1* by berberine was abrogated by *Nrf2* silencing (Fig. 6). Additionally, luciferase reporter assay and Western blotting results showed that berberine treatment increased *Nrf2* reporter gene activity and upregulated the nuclear translocation of Nrf2 in Caco-2 cells (Fig. 6), suggesting that berberine is a strong Nrf2 activator. Previous studies also demonstrated the ability of berberine to activate Nrf2

nuclear translocation and promote its protective effects in different disease models (Zhang et al., 2016; Dinesh and Rasool, 2017; Mahmoud et al., 2017). These results suggest that the P-gp induction by berberine is achieved through activation of Nrf2.

In conclusion, our data demonstrated that P-gp expression was attenuated in DSS-induced colitis rat colons. Moreover, berberine treatment markedly alleviated the inflammatory processes involved in DSS-induced colitis and improved P-gp-mediated barrier function. In vivo and in vitro results demonstrated that the induction of P-gp expression and activity by berberine may occur via activation of the Nrf2-mediated signaling pathway. The results of the current study suggest that the therapeutic effects of berberine on colitis are potentially due to the Nrf2-mediated upregulation of P-gp,

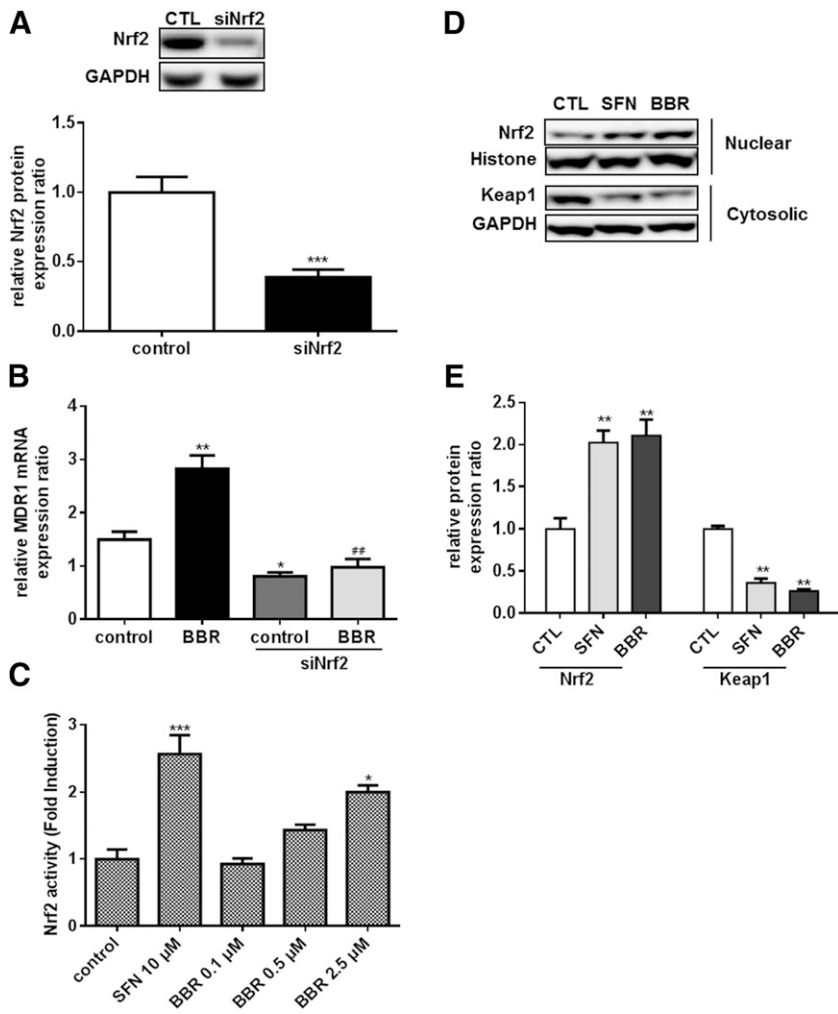


Fig. 6. Berberine upregulated the Nrf2/P-gp pathway in vitro. (A) *Nrf2* silencing efficiency was measured by Western blotting, and GAPDH was used as a loading control. Data represent the mean \pm S.E.M. of six samples from two independent experiments. *** P < 0.001 vs. control. (B) *Nrf2* knockdown abrogated P-gp induction by berberine in Caco-2 cells. qRT-PCR analysis was performed to measure mRNA expression, and data represent the mean \pm S.E.M. of six samples from two independent experiments. * P < 0.05; ** P < 0.01 vs. vehicle; ## P < 0.01 vs. berberine alone. (C) Berberine treatment increased Nrf2 reporter gene activity. Caco-2 cells were transiently transfected with the ARE-luciferase plasmid and CMV *Renilla* luciferase plasmid, followed by treatment with different concentrations of berberine (0.1, 0.5, or 2.5 μ M) or the positive agonist SFN (10 μ M) for 24 hours. * P < 0.05; *** P < 0.001 vs. control. (D and E) Representative Western blots and group data depicting nuclear translocation of Nrf2 and protein abundances of its repressor Keap1 in Caco-2 cells treated with berberine (2.5 μ M) or SFN (10 μ M) for 24 hours. Data represent the mean \pm S.E.M. of six samples from two independent experiments. ** P < 0.01 vs. control.

thereby highlighting the potential of P-gp and/or Nrf2 as new targets for IBD therapy.

Authorship Contributions

Participated in research design: Jing, Fu, Wang.

Conducted experiments: Jing, Zhang, Guo, Chen.

Performed data analysis: Jing, Wu.

Wrote or contributed to the writing of the manuscript: Jing, Safarpour, Fu.

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