Research Article

Predisposition of Neonatal Maternal Separation to Visceral Hypersensitivity via Downregulation of Small-Conductance Calcium-Activated Potassium Channel Subtype 2 (SK2) in Mice

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Received 5 June 2020; Revised 31 August 2020; Accepted 6 September 2020; Published 22 September 2020

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Background. Visceral hypersensitivity is a common occurrence of gastrointestinal diseases such as irritable bowel syndrome (IBS), wherein early-life stress (ELS) may have a high predisposition to the development of visceral hypersensitivity in adulthood, with the specific underlying mechanism still elusive. Herein, we assessed the potential effect of small-conductance calcium-activated potassium channel subtype 2 (SK2) in the spinal dorsal horn (DH) on the pathogenesis of visceral hypersensitivity induced by maternal separation (MS) in mice. Methods. Neonatal mice were subjected to the MS paradigm, an established ELS model. In adulthood, the visceral pain threshold and the abdominal withdrawal reflex (AWR) were measured with an inflatable balloon. The elevated plus maze, open field test, sucrose preference test, and forced swim test were employed to evaluate the anxiety- and depression-like behaviors. The expression levels of SK2 in the spinal DH were determined by immunofluorescence and western blotting. The mRNA of SK2 and membrane palmitoylated protein 2 (MPP2) were determined by quantitative real-time polymerase chain reaction (qRT-PCR). Electrophysiology was applied to evaluate the neuronal firing rates and SK2 channel-mediated afterhyperpolarization current (I_AHP). The interaction between MPP2 and SK2 was validated by coimmunoprecipitation. Results. In contrast to the naïve mice, ethological findings in MS mice revealed lowered visceral pain threshold, more evident anxiety- and depression-like behaviors, and downregulated expression of membrane SK2 protein and MPP2 protein. Moreover, electrophysiological results indicated increased neuronal firing rates and decreased I_AHP in the spinal DH neurons. Nonetheless, intrathecal injection of the SK2 channel activator 1-ethyl-2-benzimidazolinone (1-EBIO) in MS mice could reverse the electrophysiological alterations and elevate the visceral pain threshold. In the naïve mice, administration of the SK2 channel blocker apamin abated I_AHP and elevated spontaneous neuronal firing rates in the spinal DH neurons, reducing the visceral pain threshold. Finally, disruption of the MPP2 expression by small interfering RNA (siRNA) could amplify visceral hypersensitivity in naïve mice. Conclusions. ELS-induced visceral pain and visceral hypersensitivity are associated with the underfunction of SK2 channels in the spinal DH.

1. Introduction

Irritable bowel syndrome (IBS) is a prevalent functional gastrointestinal disorder mainly characterized by visceral hypersensitivity, of which chronic visceral pain is one of the most common symptoms [1]. Epidemiological studies suggest that the IBS prevalence reached approximately 11% worldwide, and about 94% of IBS patients presented with visceral hypersensitivity. However, with respect to the specific mechanism of visceral hypersensitivity, the complex etiological factors such as changes of immune and neuroendocrine systems, psychological and physical stresses, and genetic and early life influences still await further elucidation [2–4]. Our prior report confirmed that early-life stresses (ELS) such as colorectal distension (CRD) and maternal separation (MS) can cause visceral hypersensitivity in rats in adulthood [5–7]. In addition, clinical and preclinical data indicate that ELS is an important predisposing factor of long-term hyperalgesia [8]. Animal studies have shown that early life is a critical period for the normal development of individuals,
during which physical and psychological stresses can lead to neuroendocrine changes and exert effects on the signal pathways involved in neuroplasticity regulation, accompanied by corresponding alterations of neurobehaviors, including learning and memory and anxiety-like and depression-like behaviors [9, 10]. Moreover, ELS can reportedly exaggerate stress-induced visceral hypersensitivity via action on the hypothalamic-pituitary-adrenal (HPA) axis, the autonomic nervous system (ANS), and the epigenetic modification [11, 12]. Clinical evidence demonstrates that ELS can induce major consequences in the nervous system and plays a pivotal role in the pathophysiology of a variety of disorders, such as IBS, major depressive disorder (MDD), and posttraumatic stress disorder (PTSD), all of which can severely impede behavioral and cognitive well-being of humans [13–15]. However, a number of studies indicate that ELS (physical or psychological or both) can lead to different long-term behavioral and physiological alterations in adulthood via activation of diverse neural networks [16–18]. Of note, distinctive to the physical stress, which exerts earlier but relatively mild impact, the psychological stress renders later but more severe consequences [19]. Given the important role of early psychological life stress in predisposing individuals to physical and mental health disorders in adulthood, we adopted the scheme of MS to induce visceral hypersensitivity [20].

Visceral sensory signals are transmitted to various corticolimbic structures via parasympathetic afferent and sympathetic afferent pathways, in which the dorsal horn (DH) of the spinal cord plays a vital role via reception of visceral information from the dorsal root ganglia and relaying to the neuromatrix of the pain [21–23]. In addition, the hyperexcitability of visceral nociceptive neurons in the spinal cord DH is involved in visceral hypersensitivity [24–26]. Hence, the modulation of the excitability of these nociceptive neurons has invited intriguing approaches to the therapeutics of visceral hypersensitivity. Small-conductance calcium-activated potassium (SK) channels in dendritic spines are reportedly able to control the excitability of neuronal cells via the regulation of synaptic transmission [27].

SK channels constitute a distinct subfamily of potassium channels, which are sensitive to intracellular calcium ions with no voltage dependence [28]. SK channels are the modulators of neuronal excitability, involved in the mediation of afterhyperpolarization current ($I_{AHP}$) and the regulation of neuronal firing rates [29, 30]. Immunohistochemical findings have validated that the SK channels are widely expressed throughout the brain [31], spinal dorsal root ganglia, and spinal DH neurons [32]. With respect to their physiological and pharmacological characterization, the SK channels are categorized into three subtypes: SK1, SK2, and SK3 channels [33], with SK2 channels almost entirely located in the superficial layer of the spinal DH [32]. SK channels in the spinal DH are involved in the modulation of nociception, as illustrated by the SK channel opener 1-EBIO in mitigation of the thermal-induced nociception behavior by reducing spike discharges and increasing $I_{AHP}$ amplitudes [34]. In addition, activation of SK channels in the spinal cord can also ameliorate mechanical hypersensitivity in a rat model of inflammatory pain [35]. Conversely, intraplantar injection of a specific SK channel inhibitor induces mechanical allodynia and heat hyperalgesia in naïve rats [36]. Furthermore, the localization of SK2 channels on the cell surface membrane can be dynamically governed by the anterograde and retrograde trafficking [37]. Recently, a novel synaptic scaffold MPP2 has been reported to be responsible for locating the SK2 channel at the synapses, which allows SK2 channels to contribute to long-term potentiation (LTP) and synaptic plasticity fortification [38].

In the present study, we examined the variation of the SK2 protein expression and SK2 channel activity with western blotting and electrophysiological recording in mice presenting with MS-induced visceral hypersensitivity. The interaction between MPP2 and SK2 was determined by coimmunoprecipitation.

2. Methods and Materials

2.1. Animals. C57BL/6J mice were provided by the Experimental Animal Center of Xuzhou Medical University (Xuzhou, China), with one male mouse cohabiting with two female mice to facilitate reproduction, with controlled temperature and humidity (22°C and 50%) and ad libitum access to food and water. Model mice were exposed to maternal separation protocol, and only males were used for the experiments. All procedures were conducted in accordance with the NIH Guide for the Care and Use of Laboratory Animals (2011) and approved by the Institutional Animal Care and Use Committee at Xuzhou Medical University.

2.2. Maternal Separation Protocol. Maternal separation of pups from their dams was sustained for 6 h daily (8:00-11:00 A.M. and 2:00-5:00 P.M.), as from postnatal day 2 (P1) to day 15 (P14), with the pups of the same brood isolated in one cage (15 × 20 cm) maintained at 32 ± 0.5°C (P1-P5) or 30 ± 0.5°C (P6-P14). At the end of separation of 3 h, pups were returned to their home cages (Figure 1(a)), whereas control mice were standard facility reared [39, 40].

2.3. Reagents. The reagents were as follows: rabbit anti-SK2/KCn2.2 polyclonal antibody (APC-028, Alomone Labs, Israel), Alexa Fluor 594 donkey anti-rabbit IgG (H+L) (A21207, Thermo Fisher Scientific, Waltham, MA, USA), mouse anti-GAPDH mAb (AC001, ABclonal, Waltham, MA, USA), mouse anti-β-actin mAb (sc-47778, Santa Cruz Biotechnology, USA), HRP-labeled goat anti-rabbit IgG (H+L) (A0216, Beyotime, China), HRP-labeled goat anti-mouse IgG (H+L) (A0216, Beyotime), alkaline phosphatase goat anti-rabbit IgG (ZB-2308, Beyotime), BCA protein assay kit (P0012, Beyotime), sodium dodecyl sulfate- (SDS-) polyacrylamide gel electrophoresis (PAGE) sample loading buffer (P0015, Beyotime), BCIP/NBT alkaline phosphatase color development kit (C3206, Beyotime), BeyoECL Moon kit (P0018F0T, Beyotime), and Syn-PER™ Synaptic Protein Extraction Reagent (#87793, Thermo Fisher Scientific, Waltham, MA, USA).

2.4. Assessment of Abdominal Withdrawal Reflex (AWR) and Visceral Pain Threshold. Visceral sensitivity was assessed by AWR and visceral pain threshold [7, 41]. Mice were
structures. The visceral pain threshold was determined by the
response; 1, brief head movement followed by immobility;
2, contraction of the abdominal muscles; 3, elevation of the
pelvic region to a distension pressure (20, 40, 60, or 80 mmHg) for
a duration of 20 s at an interval of 2-3 min (Figure 1(c)).

The AWR was scored as follows: 0, absence of behavioral
stimulus intensity whereby to evoke a visible contraction of
the abdomen; and 4, body arcing and elevation of the pelvic
structures. The visceral pain threshold was defined by the
stimulus intensity whereby to evoke a visible contraction of
the abdominal wall. For accuracy, distension was conducted in
triplicate to calculate an average. In the process of behav-
ioral test, the technicians were blinded to animal grouping.

Prior to testing, mice were supplied with two bottles of tap water for the first day, followed by
replacement with the 1% sucrose solution for the second
day. On the third day, mice were deprived of water. On the
fourth day, the mice were provided with two bottles filled
with 1% sucrose solution and tap water each. Finally, sucrose
preference was calculated as the consumption volume of
sucrose solution over total volume of liquid intake.
2.8. Forced Swim Test. Each mouse was gently immerged in water at 25°C and 30 cm in depth (beyond the reach of bottom) in a plastic cylinder for 1 min adaption, with the immobility duration within 5 min recorded. Immobility is defined as the maintenance of an immobile posture in one place, or minimum paw movement necessary to keep its nose and eyes above water, with prolonged immobility duration deemed as “behavioral despair.”

2.9. Intrathecal Catheter Implantation. With the mice anesthetized under 2% pentobarbital sodium (40 mg/kg, i.p.), a longitudinal dorsal incision (approximately 1 cm) was made through the skin and muscle, with the L5-L6 vertebrae fully exposed. PE catheter (0.23 mm OD × 0.09 mm ID) containing 0.9% sterile saline was inserted between L5 and L6. Sterile saline (1 μL) was gently injected into the subarachnoid space to ensure that the catheter was unobstructed. The outside end of the catheter was sealed, and the catheter was secured to the environment. The lysate Syn-PER™ Synaptic Protein Extraction Reagent (1 mL/100 mg) and the phosphatase inhibitor phenylmethylsulfonyl fluoride (PMSF) were successively added, followed by homogenization and centrifugation at 8000 rpm for 10 min at 4°C, with 80 μL supernatant (whole-cell lysis) sampled thereafter. Then, the supernatant was centrifuged at 12000 rpm for 20 min, with the cracking buffer (20 μL) added to the particles (membrane section). The BCA method was employed to detect and trim the protein concentration after lysis. Equal amounts of protein were separated by SDS-PAGE gels and transferred onto the PVDF membrane. After blockade with 5% nonfat milk for 2 h at r/t, the PVDF membranes were incubated with anti-SK2 (1:200) and anti-GAPDH (1:1000) primary antibodies at 4°C overnight. After lavage in Tris-buffered saline with Tween (TBST), the PVDF membrane was incubated with HRP-conjugated secondary antibody (1:1000) for 2 h at r/t. Western blotting analyses were performed with ImageJ software (NIH, USA).

2.10. Electrophysiology. For in vitro recordings, 45 min after the last behavior test, mice underwent transcardial perfusion under deep anesthesia; transverse sections of the lower lumbar and upper sacral segment (L4-S4) were sliced at the last behavior test, mice underwent transcardial perfusion under 2% pentobarbital sodium (40 mg/kg, i.p.), a longitudinal dorsal incision (approximately 1 cm) was made through the skin and muscle, with the L5-L6 vertebrae fully exposed. PE catheter (0.23 mm OD × 0.09 mm ID) containing 0.9% sterile saline was inserted between L5 and L6. Sterile saline (1 μL) was gently injected into the subarachnoid space to ensure that the catheter was unobstructed. The outside end of the catheter was sealed, and the catheter was secured to the adjacent tissues. With antiseptic treatment, mice were allowed for recovery for 5 days. 1-EBIO (30 μg), apamin (0.5 ng), and small interfering RNA (siRNA) targeting MPP2 (5 μg) were administered in a volume of 5 μL via a microsyringe infusion pump (KDS Scientific, USA) loaded with a 10 μL mL Hamilton microsyringe.

2.11. Western Blotting. 45 min after the last behavior test, the mice were sacrificed, with the spinal cord at the lower lumbar and upper sacral segments (L4-S4) isolated on ice and placed in an Eppendorf (EP) tube and thereafter stored in the icy environment. The lysate Syn-PER™ Synaptic Protein Extraction Reagent (1 mL/100 mg) and the phosphatase inhibitor phenylmethylsulfonyl fluoride (PMSF) were successively added, followed by homogenization and centrifugation at 8000 rpm for 10 min at 4°C, with 80 μL supernatant (whole-cell lysis) sampled thereafter. Then, the supernatant was centrifuged at 12000 rpm for 20 min, with the cracking buffer (20 μL) added to the particles (membrane section). The BCA method was employed to detect and trim the protein concentration after lysis. Equal amounts of protein were separated by SDS-PAGE gels and transferred onto the PVDF membrane. After blockade with 5% nonfat milk for 2 h at r/t, the PVDF membranes were incubated with anti-SK2 (1:200) and anti-GAPDH (1:1000) primary antibodies at 4°C overnight. After lavage in Tris-buffered saline with Tween (TBST), the PVDF membrane was incubated with HRP-conjugated secondary antibody (1:1000) for 2 h at r/t. Western blotting analyses were performed with ImageJ software (NIH, USA).

2.12. Immunofluorescence. Mice were transcardially perfused with 0.9% saline (10 mL/10 g), followed by 4% polyformaldehyde in phosphate buffer (10 mL/10 g) after deep anesthesia. The spinal cord (L4-S4) was isolated and fixed in 4% polyformaldehyde for 24 h and equilibrated in 30% sucrose solution prior to slice preparation at a thickness of 30 μm with a cryostat (CM1800, Leica, Germany). Selected slices were thrice rinsed with PBS for 10 min and blocked with 10% donkey serum at r/t for 2 h before incubation with anti-SK2 (1:150) at 4°C for 24 h. Subsequently, the slices were lavaged thrice and incubated with Alexa Fluor 594 (1:200) at r/t for 2 h. Images were obtained with the use of a confocal laser microscope (FV1000, Olympus, Japan).

2.13. Quantitative Real-Time Polymerase Chain Reaction (qRT-PCR). 45 min after the last behavior test, mice were sacrificed under pentobarbital sodium. The spinal cord was quickly removed on ice, with the spinal cord at lower lumbar and upper sacral segment (L4-S4) dissected and total RNA extracted with Spin Column Animal Total RNA Purification Kit (Shenggong, China) as per standard protocols. RNA preparations were reverse transcribed to generate cDNA with FastKing RT Kit (TIANGEN, China). The cDNA products served as templates for real-time PCR analysis to observe the SK2 expression with the SK2-specific primers (Shenggong, China). The primers applied to amplify SK2 were 5′-CTGCCTGTGTTACTGGAATCATG-3′ (forward) and 5′-CATCAGAAATGGTGCACATGC-3′ (reverse). Sense and antisense primers were located on different exons to avoid false-positive results due to genomic DNA contamination. PCRs were performed on LightCycler 480 System via fluorescent SYBR Green technology (Applied Biosystems, USA). Reaction protocols were in the following schema: 1 min at 95°C for enzyme activation followed by 40 cycles of 10 s at 95°C and 30 s at 60°C and 30 s at 72°C, followed by 95°C for 5 s and 60°C for 60 s. Melting cure analysis was performed to check the specificity of the amplification products. All reactions contained the same amount of cDNA.
The relative expression ratio of SK2 mRNA was normalized to GAPDH gene expression using the ΔΔCt method (2^-ΔΔCt).

2.14 Coimmunoprecipitation. The lysate was centrifuged at 13000 rpm for 20 min at 4°C. The supernatant was incubated with the indicated anti-SK2 for 30 min, and then, 20 μL of protein A/G agarose beads (Thermo Scientific, USA) was added for incubation overnight at 4°C with rotation. The beads were rinsed in triplicate in immunoprecipitation lystate. Proteins were eluted with 20 μL of 2x SDS sample buffer at 37°C. Bound and eluted proteins were subsequently separated by SDSPAGE and transferred to the PVDF membrane. After blockade with 5% skim milk for 2 h, the membrane was probed with the anti-MPP2 overnight at 4°C. HRP-conjugated secondary antibody was applied for 45 min. Blot analyses were performed with ImageJ software (NIH, USA).

2.15 Statistical Analysis. Data are expressed as mean ± SEM. For independent samples, Student’s t-test and two-way analysis of variance (ANOVA) test followed by Bonferroni’s post hoc test or S-N-K multiple comparisons were employed. All statistical analyses were conducted with the SPSS 19.0 (IBM, USA) software. P < 0.05 was considered statistically significant.

3. Results

3.1 ELS Induced Visceral Hypersensitivity in Mice Undergoing Neonatal MS. The canonical model of MS serves as a preclinical model of ELS. Murine pups were separated from their dams for 6 h daily as of postnatal day 2 (P1) to day 15 (P14). At week 8 (reaching adulthood), AWR and visceral pain threshold were measured (Figures 1(a) and 1(c)). There was...
an insignificant difference in body weight between control and MS mice within 5 weeks after weaning (n = 12, P = 0.482, Figure 1(b)), suggesting that mice did not suffer from malnutrition due to MS. Neonatal MS altered the visceral pain threshold and AWR score. Mice experiencing neonatal MS presented with lower pain threshold compared with control mice (n = 12, P < 0.01, Figure 1(d)). Consistently, MS mice presented enhanced AWR score compared to control mice. We further analyzed the statistical difference in each distension pressure and identified that neonatal MS increased AWR score at pressure stimuli at 40 mmHg (P < 0.05), 60 mmHg (P < 0.01), and 80 mmHg (P < 0.05), respectively (n = 12, Figure 1(e)).

3.2 Mice with Neonatal MS Presented Anxiety- and Depression-Like Behaviors. The elevated plus maze and open field test serve to investigate the effect of MS on anxiety-like behaviors. As demonstrated by representative traces in elevated plus maze in Figure 2(a), compared with the control mice, MS mice were markedly inactive in the open arms of the maze as evidenced by decreased time (n = 8, P < 0.01, Figure 2(b)) and times of total entry in the open arms (n = 8,
Figure 4: Effects of the SK2 channel blocker apamin on $I_{\text{AH}}$, spontaneous neuronal firing rates, SK2 protein in membrane fraction, and pain threshold. (a, b) Apamin injection decreased the amplitude of $I_{\text{AH}}$ in naïve mice ($t$-test, $t = 8.97$, $P < 0.01$, $n = 15$ neurons/5 mice per group). (c, d) Apamin injection increased the neuronal firing rates in the spinal DH of naïve mice ($t$-test, $t = 2.82$, $P < 0.01$, $n = 15$ neurons/5 mice per group). (e) Apamin injection resulted in the decrease of the spinal SK2 channel in membrane fraction in the naïve mice ($t$-test, $t = 2.70$, $P < 0.05$, $n = 6$ group). (f) Apamin administration caused the decrease of the pain threshold in naïve mice ($t$-test, $t = 3.00$, $P < 0.01$, $n = 8$ group). (g) Naïve mice with intrathecal injection of apamin exhibited increased AWR score in response to the distension pressure at 60 mmHg (Bonferroni post hoc test, $P < 0.05$) (two-way ANOVA test, $F (1,14) = 3.82$, $P = 0.07$, $n = 8$ per group). Data are expressed as mean ± SEM; *$P < 0.05$ and **$P < 0.01$.

$P < 0.05$, Figure 2(c)). The same total distance of travel between the control and MS mice authenticated the intactness of motor ability ($n = 8$, $P = 0.783$, Figure 2(d)). Mice with neonatal MS exhibited significantly diminished duration in the central area ($n = 8$, $P < 0.05$, Figures 2(e) and 2(f)) and distance covered in the central area ($n = 8$, $P < 0.05$, Figures 2(e) and 2(g)) compared with the control group, with no significant difference in the total distance of travel between the control and MS mice ($n = 8$, $P = 0.653$, Figures 2(e) and 2(h)). The results of the elevated plus maze and open field test indicated MS mice had attenuated exploration attempt and remained close to the walls compared with the control mice. To verify whether MS mice exhibited depression-like behaviors, the reward-based sucrose preference test and forced swim test were involved. Compared to the MS mice, the control mice had a significant preference for sucrose ($n = 8$, $P < 0.05$, Figures 2(i) and 2(j)), indicating the presence of depression-like behaviors in the MS mice. In addition, we measured the perseverence of mice to identify a depressive phenotype, via the forced swim test. The results revealed that MS mice exhibited increased percentage of immobility duration in the total time compared with the control mice ($n = 8$, $P < 0.05$, Figures 2(k) and 2(l)). Thus, these data indicated that mice experiencing neonatal MS presented the anxiety- and depression-like behaviors.

3.3. The Decline of SK2 Protein in Membrane Fraction, SK2 mRNA, and $I_{\text{AH}}$ in Spinal DH in Mice Experiencing Neonatal MS. Western blotting data showed that the spinal SK2 protein in the membrane fraction presented a significant decrease in the MS mice compared with the control mice ($n = 6$, $P < 0.05$, Figure 3(a)). However, there was no difference in the total spinal SK2 protein between the two groups ($n = 6$, $P = 0.157$, Figure 3(b)). Consistently, the same was also true of the total spinal SK2 mRNA ($n = 9$, $P = 0.877$, Figure 3(c)). The expression of SK2 showed that the SK2 channel is widely expressed across the spinal dorsal horn in either the control mouse or mice with neonatal MS, and there was no difference in the number of SK2+ neurons in the spinal dorsal horn between the two groups ($n = 4$, $P = 0.783$, Figures 3(d) and 3(e)). Mice with neonatal MS presented lower $I_{\text{AH}}$ compared to mice without neonatal MS. The average peak amplitude of $I_{\text{AH}}$ was $45.35 \pm 2.49$ pA and $31.13 \pm 2.32$ pA in the control and MS mice, respectively ($n = 16$ neurons/5 mice, $P < 0.01$, Figures 3(g) and 3(h)). Consistently, mice with neonatal MS presented an increase in spontaneous neuronal firing rates versus control mice ($2.54 \pm 0.25$ vs. $4.03 \pm 0.26$, $n = 15$ neurons/5 mice, $P < 0.01$, Figures 3(i) and 3(j)). The above results suggested that the function of the SK2 channel in MS mice was mitigated due to the experience of ELS, which led to increased neuronal
activity in the spinal DH and ultimately visceral hypersensitivity.

3.4. Effects of SK2 Channel Blocker Apamin on $I_{\text{AHP}}$, Spontaneous Neuronal Firing Rates, and Visceral Pain Threshold. SK2 channel blocker apamin was added into the ACSF to reach the desired concentration (100 nM) which decreased $I_{\text{AHP}}$ in mice without neonatal MS versus the control group (47.86 ± 2.65 vs. 19.65 ± 1.70, n = 15 neurons/5 mice, $P < 0.01$, Figures 4(a) and 4(b)) and increased the neuron firing rates (2.81 ± 0.24 vs. 3.85 ± 0.28, n = 15 neurons/5 mice, $P < 0.01$, Figures 4(c) and 4(d)). Western blotting data showed that the spinal SK2 protein in the membrane fraction presented a significant decrease in mice receiving apamin ($n = 6$, $P < 0.05$, Figure 4(e)). AWR and visceral pain threshold were measured 2 h after intrathecal administration of apamin (0.5 ng/5 μL), and the results showed that apamin administration contributed to the decrease in visceral pain threshold ($n = 8$, $P < 0.01$, Figure 4(f)). Subsequent to apamin administration, naïve mice presented increased AWR score with pressure stimulus at 60 mmHg versus the ACSF control group ($n = 8$, $P < 0.05$, Figure 4(g)).

3.5. Effects of SK2 Channel Blocker Apamin on Anxiety- and Depression-Like Behaviors. Behavioral tests were measured 2 h after intrathecal administration of apamin (0.5 ng/5 μL), and the results showed that apamin administration did not affect the anxiety-like behavior of mice. The duration spent in the open arms ($n = 8$, $P = 0.657$, Figures 5(a) and 5(b)), the times of entry into the open arms ($n = 8$, $P = 0.725$, Figures 5(c) and 5(d)), and the total distances travelled ($n = 8$, $P = 0.777$, Figures 5(e) and 5(f)) between the two groups ($n = 8$ per group). The percentage of the sucrose intake volume over the total fluid intake volume in mice with apamin injection was consistent with that in control mice ($t = 0.42, P = 0.679, n = 8$ per group) (k).
decline in the visceral pain threshold in mice experiencing prior to behavioral tests. 1-EBIO administration reversed the μ
got intrathecal administration of 1-EBIO (30 μg/5 μL) 2 h prior to behavioral tests. 1-EBIO administration reversed the
in the visceral pain threshold in mice experiencing neonatal MS (n = 8, P < 0.01; Figure 6(f)). Consistently, subsequent to 1-EBIO administration, MS mice presented decreased AWR score versus dimethyl sulfoxide (DMSO) control group. With the incremental stimuli of distension pressures, MS mice exhibited decreased AWR scores at 40 mmHg (P < 0.05) and 60 mmHg (P < 0.01) after the administration of 1-EBIO (n = 8, Figure 6(g)).

3.6. Effects of SK2 Channel Activator 1-EBIO on Visceral Hypersensitivity due to Neonatal MS in Mice. SK2 channel activator 1-EBIO was added into the ACSF to reach the desired concentration (100 μM). 1-EBIO elevated I_{AHP} (31.81 ± 2.24 vs. 43.41 ± 2.71, n = 15 neurons/5 mice, P < 0.01, Figures 6(a) and 6(b)) and decreased the neuron firing rates (4.29 ± 0.27 vs. 2.73 ± 0.23, n = 15 neurons/5 mice, P < 0.01, Figures 6(c) and 6(d)) in the spinal DH neurons. Western blotting data showed that the spinal SK2 protein in the membrane fraction presented a significant increase in mice receiving 1-EBIO (n = 6, P < 0.05, Figure 6(e)). Mice underwent intrathecal administration of 1-EBIO (30 μg/5 μL) 2 h prior to behavioral tests. 1-EBIO administration reversed the
decline in the visceral pain threshold in mice experiencing neonatal MS (n = 8, P < 0.01; Figure 6(f)). Consistently, subsequent to 1-EBIO administration, MS mice presented decreased AWR score versus dimethyl sulfoxide (DMSO) control group. With the incremental stimuli of distension pressures, MS mice exhibited decreased AWR scores at 40 mmHg (P < 0.05) and 60 mmHg (P < 0.01) after the administration of 1-EBIO (n = 8, Figure 6(g)).

3.7. Effects of SK2 Channel Activator 1-EBIO on Anxiety- and Depression-Like Behaviors. Mice underwent intrathecal administration of 1-EBIO (30 μg/5 μL) 2 h prior to behavioral tests. Similar to apamin injection, 1-EBIO administration did not affect the anxiety-like behavior of mice. The duration spent in the open arms (n = 8, P = 0.735, Figures 7(a) and 7(b)), the times of entry into the open arms (n = 8, P = 0.425, Figures 7(a) and 7(c)), the duration in central area (n = 8, P = 0.725, Figures 7(e) and 7(f)), and the courses in the central area (n = 8, P = 0.866, Figures 7(e) and 7(g)) showed insignificant differences between the control mice and mice with 1-EBIO injection. Similarly, 1-EBIO administration did not affect the depression-like behavior as evidenced by the same preference for sucrose (n = 8, P = 0.975, Figures 7(i) and 7(j)) and immobility duration (n = 8, P = 0.984, Figures 7(k) and 7(l)) between the two groups.
3.8. Contribution of Downregulated MPP2 to the Downregulation of Membrane SK2 Protein. To further explore the mechanism of SK2 downregulation in MS mice, we focused on MPP2, which is a synaptic scaffold protein located in postsynaptic density (PSD), and SK2 acts by anchorage on the synaptic membrane via MPP2. As depicted in Figure 8(a), with coimmunoprecipitation, we identified that SK2 interacted with MPP2. Western blotting data revealed a significant decrease of the spinal MPP2 protein in the membrane fraction in mice experiencing neonatal MS (n = 6, P < 0.05, Figure 8(b)). In addition, qRT-PCR, western blotting data, and behavioral tests further confirmed our speculation that MPP2 downregulation contributed to the decrease in the membrane SK2 protein. The naïve mice were injected with either siRNA of MPP2 or the negative control (NC) of siRNA, and the aforementioned tests were conducted 30 h thereafter. qRT-PCR data showed that spinal MPP2-related mRNA presented a significant decrease following the siRNA targeting MPP2 administration (n = 6, P < 0.01, Figure 8(c)). Consistently, the same was also true of the membrane MPP2 (n = 6, P < 0.01, Figure 8(d)) and SK2 protein in membrane fraction (n = 6, P < 0.01, Figure 8(e)). The visceral pain threshold in naïve mice presented a significant decrease following injection of the siRNA targeting MPP2 (n = 8, P < 0.05, Figure 8(f)). Consistently, after injection of the siRNA targeting MPP2 in naïve mice, the AWR score was significantly increased with pressure stimulus at 40 mmHg (n = 8, P < 0.05, Figure 8(g)). Taken together, these results suggested that the downregulation of MPP2 may serve to explicate the downregulated membrane SK2 protein in mice experiencing neonatal MS.
4. Discussion

SK channels in the spinal DH play vital roles in nociception modulation [34–36]. In this study, we investigated the role of SK2 channels in the spinal DH in visceral hypersensitivity induced by maternal separation. The present findings provided evidence that mice experiencing neonatal MS were susceptible to visceral stimuli in adulthood, along with significant downregulation of the spinal membrane SK2 channel protein and SK2-mediated I\(_{\text{AHP}}\), and an increase in neuronal firing rates in the spinal DH. Application of SK2 channel blocker apamin could exacerbate visceral hypersensitivity by reducing I\(_{\text{AHP}}\) and increasing neuronal firing rates in naïve mice. Intrathecal injection of SK2 channel activator 1-EBIO alleviated visceral hypersensitivity and reversed the alteration of I\(_{\text{AHP}}\) and neuronal firing rates in mice experiencing MS. MPP2 could interact with SK2, accompanied by a downregulation of the membrane MPP2 protein expression in mice exposed to MS. In addition, disruption of MPP2 by siRNA aggravated visceral pain in naïve mice. These findings were in line with prior evidence that SK2 channels in the spinal DH are involved in visceral hypersensitivity induced by ELS [42].

Adverse experiences in early life can affect the formation of neuronal circuits and exert long-term effects on neuronal function, which is deemed as a potential risk factor of increased physical and psychological morbidity in adulthood [43]. Accumulating evidence has authenticated that ELS can lead to corresponding abnormalities of learning and memory as well as anxiety- and depression-like behaviors [9, 10]. These reports are supportive of our finding that mice exposed to MS exhibited anxiety- and depression-like behaviors. The anxiety-like behavior tests in our study included open field test and elevated plus maze test in parallel with sucrose preference test and forced swimming test to verify depression-like behaviors. Moreover, the stressor patterns can be divided into two major categories: physical (which actually disturbs physiological state) and psychological (which threatens the current or expected status) [18, 19]. Early physical and psychological life stresses can lead to different long-term behavioral and physical alterations by activation of diverse neural networks [16–18], both contributing to changes of neuroendocrine and signal

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**Figure 8:** The downregulation of MPP2 contributed to the decrease in the membrane SK2 channel protein and visceral pain threshold. (a) From western blotting of spinal cord cell lysates expressing anti-MPP2 antibody and immunoprecipitation with SK2 or IgG (control), adjacent blotting showed input of MPP2. (b) Spinal MPP2 protein in the membrane fraction presented a significant decrease following the siRNA targeting MPP2 administration (t-test, \( t = 2.25, P < 0.05, n = 6 \) per group). (c) Spinal MPP2-related mRNA presented a significant decrease following the siRNA targeting MPP2 administration (t-test, \( t = 3.56, P < 0.01, n = 6 \) per group). (d) The siRNA targeting MPP2 injection resulted in the decrease of spinal membrane MPP2 protein in naïve mice (t-test, \( t = 3.59, P < 0.01, n = 6 \) per group). (e) The siRNA targeting MPP2 administration led to the decrease of spinal SK2 channel in the membrane fraction (t-test, \( t = 3.54, P < 0.01, n = 6 \) per group). (f) The visceral pain threshold in naïve mice presented a significant decrease after injection of the siRNA targeting MPP2 (two-way ANOVA test, \( F (1, 14) = 3.76, P = 0.07, n = 8 \) per group). (g) The AWR score presented a significant increase in naïve mice subjected to pressure stimulus at 40 mmHg (Bonferroni post hoc test, \( P < 0.05 \)) after injection of the siRNA targeting MPP2 (two-way ANOVA test, \( F (1, 14) = 3.76, P = 0.07, n = 8 \) per group). Data are expressed as mean ± SEM; *\( P < 0.05 \) and **\( P < 0.01 \).
pathways involved in regulating neuroplasticity. In addition, behavioral abnormalities include somatic and visceral hyperalgesia [11, 12, 44, 45]. Our findings were in line with these studies that mice experiencing MS developed visceral hypersensitivity.

As is well acknowledged, visceral information originating from the distal colon and rectum can be converged to the thoracolumbar and sacral segments of the spinal cord, whereas a number of thoracolumbar spinal neurons can also receive input from afferents of the superficial skin and deep somatic domain [46]. Accordingly, the spinal cord is highly subjected to modulation of somatic and visceral sensory afferents. Structural and functional abnormalities of spinal DH neurons are involved in inflammatory pain, neuropathic pain, and other pain disorders [47, 48]. Moreover, the visceral nociceptive neurons in the spinal DH reportedly exhibit hyperexcitability in animal subjects with visceral hypersensitivity [24–26], which invites further exploration of the mechanism of spinal DH involved in visceral hypersensitivity.

In this study, we adopted maternal separation to establish the animal model of visceral hypersensitivity. Separation of pups from their dams was conducted daily for 6 h as of postnatal day 2 to 15, with distinction from studies of MS models established by separating pups from their dams 3 h daily. As per their findings, separation for 3 h daily can develop somatic and visceral hyperalgesia as well [49–52]. Nevertheless, we have recognized that exposure to MS 3 h daily could not develop visceral hypersensitivity in adulthood, whereas separation for 6 h daily could successfully induce visceral hypersensitivity, which was contrary to the abovementioned results [51, 52] and consistent with our previous reports [53]. We attributed this discrepancy to the distinction in time course of separation and animal species.

Our data revealed that mice exposed to maternal separation presented a significant expression downregulation of the spinal membrane SK2 channel protein and SK2-mediated $I_{\text{AHP}}$. Synaptic SK2-containing channels can modulate the induction of synaptic plasticity and excitatory postsynaptic responses, due to the activation by synaptically evoked Ca$^{2+}$ influx [38]. Our study indicated that the downregulation of the membrane SK2 channel protein expression contributed to an elevation of neuronal excitability which was validated by an increase in neuronal firing rates in spinal DH. The SK channels mediate medium $I_{\text{AHP}}$ conductances in neurons across the central nervous system, which is involved in the regulation of neuronal firing, domination of LTP, and modulation of memory activities [54]. Moreover, the enhancement of the SK2 channel function in the spinal cord can attenuate the thermal stress-induced nociceptive behavior by reducing spike discharges and increasing $I_{\text{AHP}}$ amplitudes [34]. In contrast, intrathecal injection of specific SK channel inhibitor apamin can lead to SK2-mediated $I_{\text{AHP}}$ downregulation with a decrease in visceral pain threshold in mice experiencing colorectal distension [42].

In line with prior reports, our data confirmed that SK2 channel activator 1-EBIO could prevent the development of visceral hypersensitivity and reverse the changes of $I_{\text{AHP}}$ and neuronal firing rates in mice subjected to MS; SK2 channel blocker apamin induced visceral hyperalgesia by reducing $I_{\text{AHP}}$ and increasing neuronal firing rates in naïve mice. In addition, western blotting results revealed that intrathecal injection of 1-EBIO or apamin could result in an increase or a decrease in the membrane SK2 channel protein expression in spinal DH, which further supports the notion that the function of membrane SK2 channels is closely associated with neuronal excitability, whereby exerting effects on visceral hypersensitivity. Similar to SK2 channels, high levels of SK3 channels are identified in the spinal DH, particularly in laminae I and II [31]. However, our previous study of the SK3 channel in spinal DH vetoed the involvement of the SK3 channel in visceral hypersensitivity [42]. On this ground, we excluded the SK3 channel as our research target in this study.

Moreover, since MS could induce anxiety- and depression-like behaviors, it would be of interest whether modulation of the membrane SK2 expression in the spinal DH could lead to the alteration of these behavior phenotypes. Paradoxically, our findings indicated that the SK2 channel in the spinal DH was not involved in the modulation of anxiety- and depression-like behaviors. However, it has been reported that SK2 channel overexpression in basolateral amygdala-projecting neurons prevents stress-induced anxiety-like behavior [55]. In addition, ELS can induce anxiety- and depression-like behaviors via dysregulation of the neuroendocrine system which includes the HPA axis and the serotonergic system, along with changes of brain-derived neurotrophic factor expression [56–59]. Overactivation of the immune system can also lead to the abnormalities in anxiety- and depression-like behaviors [60]. We attributed this discrepancy in the behavior to the distinction of designation of modulation targets, which invites our future exploration.

Given the absence of significant differences in the expression of SK2 mRNA and total SK2 channel protein in the spinal DH in mice experiencing MS versus the control group and the presence of significant difference in the membrane SK2 channel protein expression in MS model mice, we further explored the molecular mechanism of the synaptic localization of the SK2 channel in the spinal DH. MPP2 is a novel synaptic scaffold, which is localized in postsynaptic sites in hippocampal neurons by binding to the abundant postsynaptic scaffold proteins such as PSD-95 and guanylate kinase-associated protein (GKAP) [61]. Moreover, MPP2 has been recently demonstrated to be responsible for proper synaptic localization and function of SK2-containing channels in hippocampal CA1 pyramidal neurons [38]. In our study, coimmunoprecipitation findings affirmed that MPP2 could interact with SK2 in the spinal cord DH, along with a decrease in the membrane MPP2 protein expression. Furthermore, disruption of the MPP2 expression by intrathecal injection of siRNA exacerbated visceral hypersensitivity in MS model mice, which further supported the role of MPP2 involved in visceral hypersensitivity. However, there are reports that synaptic membrane-associated guanylate kinase (MAGUK) proteins can influence N-methyl-D-aspartate receptor- (NMDAR-) mediated synaptic function and associated persistence of pain by regulating surface and synaptic NMDAR trafficking at the spinal cord level [62–64]. Therefore, the interactions between MPP2 and SK2 in the spinal DH in the modulation of visceral hypersensitivity await further exploration.
5. Conclusions

In conclusion, we explored the contribution of SK2 channels in the spinal DH to visceral hypersensitivity in mice. Our research has demonstrated that neonatal MS leads to visceral hypersensitivity via the downregulation of SK2 channels. Pharmacological activation of SK2 channels can prevent the precipitation of visceral hypersensitivity, and blockade of SK2 channels can aggravate visceral hypersensitivity. Moreover, the downregulation of MPP2 may underlie the decrease in membrane SK2 channels. This study may unveil one potential pathogenesis of IBS and may provide a novel avenue to the development of therapeutic agents for IBS and visceral hypersensitivity with efficiency and efficacy.

Data Availability

Raw data were generated with the use of the ImageJ software (NIH, USA), Clampex and Clampfit 10 (Axon Instruments, San Jose, CA, USA), etc. Derived data to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

All authors declare no financial competing interests.

Authors’ Contributions

Ke Wu, Jing-hua Gao, and Rong Hua contributed equally to this work.

Acknowledgments

This study was supported by grants from the National Natural Science Foundation of China (Nos. 81771203 and 81772065), Key Subject of Colleges and Universities Natural Science Foundation of Jiangsu Province (No. 19KJA110001), and Postgraduate Research & Practice Innovation Program of Jiangsu Province (No. KYCX20_2476) and sponsored by Qing Lan Project.

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