Regenerative Therapy 21 (2022) 139–147

Contents lists available at ScienceDirect

Regenerative Therapy

journal homepage: http://www.elsevier.com/locate/reth

Original Article

lncRNA NEAT1-let 7b-P21 axis mediates the proliferation of neural stem cells cultured *in vitro* promoted by radial extracorporeal shock wave

Kun Han [a, 1], Nan Kang [a, 1], Xiaotong Yu [b], Jie Lu [c, **], Yuewen Ma [a, *]

[a] Department of Rehabilitation Medicine, The First Hospital of China Medical University, Shenyang, Liaoning, PR China
[b] Institute of Meta-Synthesis Medicine, Beijing, PR China
[c] Department of Human Anatomy, College of Basic Medical Sciences, China Medical University, Shenyang, Liaoning, PR China

ARTICLE INFO

Article history:
Received 14 February 2022
Received in revised form
7 June 2022
Accepted 16 June 2022

Keywords:
let 7b
Neural stem cells
NEAT1
P21
rESW

ABSTRACT

In previous studies, we found radial extracorporeal shock wave (rESW), can promote the proliferation of neural stem cells (NSCs). Emerging evidence suggests that lncRNA NEAT1 can regulate NSCs proliferation. Whether lncRNA NEAT1 plays a role in the proliferation of NSC induced by shock waves is unclear. Cell Counting Kit-8 (CCK 8) method was used to detect the proliferation of NSCs, and the relative protein and mRNA expression of related genes of Nestin, Cyclin D1 and P21 were detected by Western Blot and Quantitative real-time PCR (RT-qPCR) respectively. Immunofluorescence staining was used to observe the changes in the number of BrdU/nestin positive cells. Overexpression of NEAT1 and let 7 b in cells were used to explore whether rESW can rescue the decreased number of NSCs.We found that the optimal dose of R15 transmitter promoting NSCs proliferation is 1.5 bar, 500 pulse, 2 Hz. 1.2–1.5 bar showed a dose-dependent effect on the proliferation of NSCs, but it was negatively correlated with the proliferation effect of NSC when it was more than 1.5 bar. We revealed that let 7 b-P21 axis was involved in regulating the inhibition of NSC proliferation which was activated by NEAT1 in NSCs. In addition, we demonstrated that rESW treatment resulted in the decrease of NEAT1 expression, which was accompanied by the improved biological function including proliferation. Our results confirm that low-intensity rESW (1.5 bar , 500 pulse , 2 Hz) can promote the proliferation of NSCs through NEAT1-let 7 b-P21 axis.

1. Introduction

Central nervous system (CNS) injuries are mainly caused by cerebrovascular accidents or mechanical contusions (for example, traumatic brain injury, TBI). Although the etiology is different, the common feature after injury is the loss of neurons [1,2]. It is believed that the nerve cells of the CNS of mammals lose their ability to regenerate shortly after birth, and the neuron loss caused by various reasons such as trauma and tumor can only be replaced by the proliferation of glial cells due to intracellular and extracellular factors that hinder neural regeneration [3,4]. This long hold concept has greatly restricted the development of treatment methods for neurological diseases. Currently, the available treatment options for CNS injury are limited, to palliative care [5]. The discovery of neural stem cells (NSCs) provides new possibilities for the treatment of CNS injury. NSCs could differentiate into neurons and glial cells under specific conditions [6,7]. Adult NSCs in mammalian brains are mainly distributed in two areas——the subventricular zone (SVZ) of the anterior horn of the lateral ventricle and the subgranular layer (SG) of the dentate gyrs in the hippocampus [8]. These cells could be used as source cells for regeneration by in situ induction with foreign factors.

Abbreviations: NSCs, Neural stem cells; rESW, radial extracorporeal shock wave; TBI, traumatic brain injury; LncRNA, Long non-coding RNA; Neat 1, nuclear-enriched abundant transcript 1; q-PCR, Quantitative real-time PCR; CCK 8, Cell Counting Kit-8; ANOVA, Analysis of variance.

* Corresponding author. Department of Rehabilitation Medicine, The First Hospital of China Medical University, Shenyang, Liaoning, PR China.
** Corresponding author. Department of Human Anatomy, College of Basic Medical Sciences, China Medical University, Shenyang, Liaoning, PR China.
E-mail addresses: lvjie@cmu.edu.cn (J. Lu), yuewen_m@126.com (Y. Ma).
Peer review under responsibility of the Japanese Society for Regenerative Medicine.
[1] Kun Han and Nan Kang contributed equally to this work.

https://doi.org/10.1016/j.reth.2022.06.006

Radial extracorporeal shock wave (rESW), as a kind of mechanical wave, has been widely used in rehabilitation medicine and orthopedics. Its therapeutic effects on bedsores, fractures, tendon injuries, aseptic inflammation and other diseases have been extensively confirmed by basic research and clinical trials [9–12]. Currently, rESW has achieved significant results in the field of regenerative medicine. In osteoarthritis (OA) , rESW combined with adipose-derived mesenchymal stem cells (ADMSCs) exhibited increased trabecular thickness and bone volume. The reduction of caspase-3 and platelet-derived growth factor (PDGF)-BB were also observed [13]. In a model of cultured fetal rat metatarsals, Sowmya R, etc. demonstrated that rESWT increased longitudinal bone growth by locally inducing chondrogenesis [14]. Our previous studies have found that rESW can promote the proliferation and differentiation of NSCs, but the specific molecular mechanism needs to be further clarified [15].

Recently, some studies have indicated that epigenetic modifications, such as DNA methylation, histone modification and non-coding RNA (ncRNA) are important factors affecting the development of the nervous system [16]. As a target gene of P53, lncRNA nuclear paraspeckle assembly transcript 1 (NEAT1) is a long non-coding RNA (lncRNA) essential for regulating the fate of stem cells [17,18]. Previous studies have shown that let 7 b prolongs the cell cycle by inhibiting the expression of Cyclin D1—presumably due to increased expression of Pten, which is a negative regulator of Cyclin D1, thereby inhibiting the proliferation of NSCs [19]. At present, although some studies used dual luciferase reporter gene experiments have shown that NEAT1 and let 7 b can interact with each other [10]; whether the interaction between NEAT1 and let 7 b regulates the proliferation of NSCs is not fully understood. Similarly, researchers have found that there is an interaction between let 7 b and P21 in liver cancer cells [20]; but they still cannot clearly explain how the two regulate the proliferation of NSCs. P21 is an important member of the Cyclin-dependent kinase inhibitor family. It regulates cell cycle, DNA replication and repair by inhibiting the activity of Cyclin-dependent kinases (Cyclin-dependent kinases CDKs) complex, and then regulating cell fate [21,22].

Therefore, based on our previous experiment, the current explored whether the lncRNA NEAT1-let 7 b-P21 axis mediates the promotion of NSCs proliferation by rESW.

2. Methods

2.1. Cell culture

NE-4C (Procell CL-0660) were provided by Procell Life Science & Technology Co.,Ltd (Wuhan, China). Mouse NSCs were grown in Dulbecco's minimal essential medium with high glucose (DMEM), supplemented with 10% fetal bovine serum. Cells were cultured according to culture method guidelines and incubated at 37 °C, 5% CO2. NE-4C cells were dissociated with 0.05% trypsin–EDTA and resuspended in the incubator supplemented DMEM described above. Cells from passage levels 4–5 were used in the present study. The cell culture medium was refreshed every 1–2 days.

2.2. Cell proliferation test

To investigate the possible impact of rESWT on the viability/proliferation of NE-4C cells, different doses of rESWT (R15, from 1.2 bar to 1.6 bar, 500 impulses, and 2 Hz) were used in the cultures. The proliferation of NE-4C cells was analyzed by Cell Counting Kit-8 (CCK 8, Sevenbio, Beijing, China) proliferation assay. After being treated with rESWT, 5×10^3 cells were seeded into 96-well plates to grow for 12 h, 24 h, 36 h, 48 h, 60 h, and 72 h. Then, 10 μL of CCK 8 was added to each well, and culture plates were incubated at 37 °C for 1 h. The absorbance was measured by photometry at 450 nm. We chose 1.5 bar, 500 impulses, 2 Hz as a therapeutic dose.

2.3. rESWT treatment

To evaluate the influence on cell proliferation *in vitro*, rESWT (R15 transmitter, STORZ MEDICAL AG, Switzerland) was applied to the cultures at a dose of 1.5 bar, 500 impulses, and 2 Hz, which maximized the therapeutic effects without significant reduction of the cell viability. NE-4C cells were dissociated with 0.05% trypsin–EDTA and resuspended in the tube supplemented DMEM described above. Transferred the cell suspension filled with the complete medium to a 2 mL EP tube. After removing the air in the tube, then embedded the EP tube into a 50 mL centrifuge tube filled with coupling agent. Coupling was used to minimize the loss of shock wave energy at the interface between the transmitter and tube. The transmitter of rESWT acted vertically on the upper part (Fig. 1A–C). The control group was maintained under the same culture conditions, but without rESWT exposure.

2.4. Cell transfection

The mimic targeting let 7 b and the negative control were obtained from *General Biol Co., Ltd* (Anhui, China). The NEAT1 overexpression plasmid vector was constructed by *HanBio Co., Ltd* (Shanghai, China). Transient transfection of mimics (100 nM) and plasmid vector (10 nM) was performed using Lipofectamine 2000 (Thermo Fisher, CA, USA) according to the manufacturer's instructions. The empty vector and negative control of siRNA were also used as control. Transfected cells were harvested at 48 h after transfection for subsequent analysis and detection.

2.5. Experiment grouping

To explore whether NEAT1 mediates rESW regulation of NSCs proliferation, we divided the experiment groups into blank control group (Control) , negative control group (Blank , plasmid, BP), overexpressing lncRNA NEAT1 (NEAT1) group, shock wave treatment group (rESW), shock wave + negative control group (rESW + BP), shock wave + overexpressing lncRNA NEAT1 group (rESW + NEAT1). Similarly, for let 7 b, we divided the experiment groups into: blank control group (Control), negative control group (negative mimic, NM), shock wave treatment group (rESW), shock wave + negative control group (rESW + NM), shock wave + overexpression let 7 b group (rESW + let 7 b).

2.6. Quantitative real-time PCR

Total RNA was isolated from the NE-4C using TRIzol (TransGen Biotech, Beijing, China) according to the manufacturer's instructions. Then, *1 μg* of total RNA was used for reverse transcription using a One-Step gDNA Removal and cDNA Synthesis SuperMix (TransGen Biotech) according to manufacturer's instructions. Green qPCR SuperMix (TransGen Biotech) was used to qualify the expression levels of *Nestin*, *Cyclin D1*, and *P21*. Glyceraldehyde 3-phosphate dehydrogenase (GAPDH) and β-actin were respectively used as endogenous controls (Sangong Biotech, Shanghai, China). Next, quantitative RT-PCR was performed using mmu-miR-let 7 b-specific probes and specific gene primers (Sangong Biotech, Shanghai, China). All qRT-PCR reactions were performed using the Step ONE Plus RT-PCR System (Applied Biosystems, USA). The relative quantification 2-ΔΔCt method was applied to calculate the gene expression values. Primers and probes used in this study are shown in Table 1.

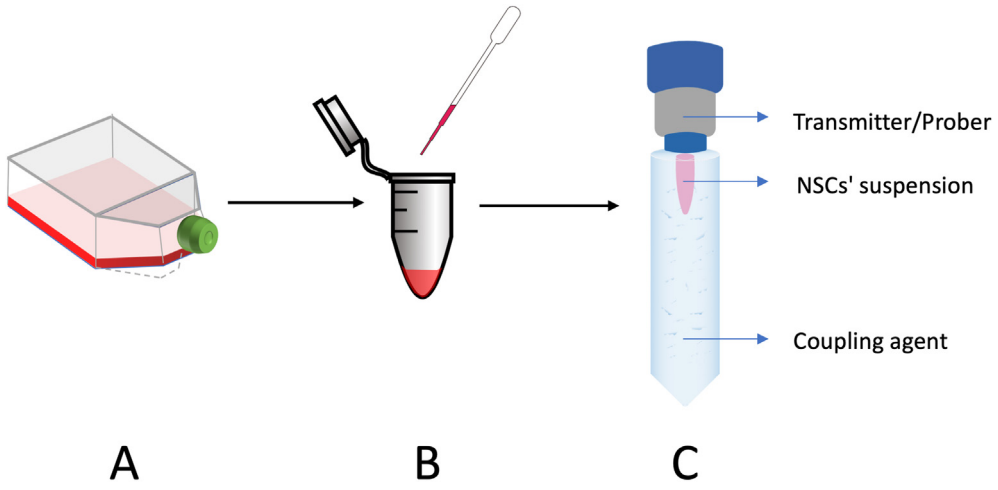

Fig. 1. Representative images showing the protocols (A) NE-4C cells are dissociated with 0.05% trypsin–EDTA and resuspended in the tube supplemented DMEM (B) The cell suspension filled with the complete medium was transferred to a 2 mL EP tube (C) After the air is removed in the tube, the EP tube is embedded into a 50 mL centrifuge tube filled with coupling agent. The transmitter of rESWT acts vertically on the upper part.

2.7. Western Blot

Total protein was extracted from cells using ice-cold radioimmunoprecipitation assay (RIPA) buffer (Sevenbio, Beijing, China) supplemented with protease inhibitors (10 mg/mL aprotinin, 10 mg/mL phenyl-methylsulfonyl fluoride [PMSF], and 50 mM sodium orthovanadate). The BCA protein assay kit (Beyotime Institute of Biotechnology) was used to determine the protein concentration of the supernatant. Equal amounts of protein samples (*30 μg*) were separated by sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) and electrically transferred onto polyvinylidene difluoride (PVDF) membrane (Millipore, Shanghai, China). Non-specific binding was blocked by incubation with 5% fat-free milk in Tris-buffered saline containing 0.1% Tween-20 (TBST) at room temperature for 2 h.

The membranes were subsequently incubated with primary antibodies as follows: *Nestin* (1:500; Proteintech, Chicago, IL, USA), *P21* (1:500; Proteintech), *Cyclin D1* (1:5000; Proteintech), and GAPDH (1:3000; Affinity, Cincinnati, OH, USA) at 4 °C overnight. The membranes were washed and incubated with HRP-conjugated secondary antibodies (Sevenbio, Beijing, China), diluted at 1:3000 at room temperature for 2 h. Immunoblots were visualized using an enhanced chemiluminescence kit (ECL; Sevenbio, Beijing, China) and detected by Bio-Rad Chemi-Doc (Bio-Rad, CA, USA) and then normalized to that of GAPDH or β-actin.

2.8. Immunofluorescence staining

Add BrdU working solution 1 h before cell fixation. Cells grown on coverslips were fixed with 4% paraformaldehyde, followed by treatment with 0.1 M glycine for 20 min at 25 °C and 0.1% Triton X-100 for additional 5 min at 25 °C to permeabilize. Cells were then incubated alternatively with the following primary antibodies: *Nestin* (1:500, Abcam, USA), *Brdu* (1:200, Abcam, USA), The primary antibodies were washed with PBS, and the cells incubated with goat anti-rat IgG-Dylight 594 (1:100 in PBS; A23440, Amylet Scientific, Wuhan, China) and goat anti-rabbit IgG-FITC (1:150; Abcam, USA) for 30 min at 25 °C. The cell nuclei were counterstained with Hoechst 33,342 (1:500; C0030, Solarbio, Beijing, China). Coverslips were finally mounted with Mowiol in PBS for observation. Images were taken with an Olympus BX51 microscope. Observations were made in 10 microscopic fields randomly taken from three different experiments.

Table 1
Primers and probes used in this study.

Neat 1-F	5′- GGCAGGTCTAGTTTGGGCAT-3′
Neat 1-R	5′- CCTCATCCCTCCCAGTACCA-3′
let 7 b-F	5′-GCGCGCTATACAACCTACTGC-3′
let 7 b-R	5′- AGTGCAGGGTCCGAGGTATT -3′
Nestin-F	5′-CAACCACAGGAGTGGGAACT-3′
Nestin-R	5′-TCTGGCATTGACTGAGCAAC-3′
P21–F	5′-CCTGGTGATGTCCGACCTG-3′
P21-R	5′-CCATGAGCGCATCGCAATC-3′
Cyclin D1-F	5′-CAGACCTCTTAACCTTATAG-3′
Cyclin D1-R	5′-TTCCCAAGCACCTCATACTACCAGC- 3′;

2.9. Single-cell clone

To clarify the stemness of NSCs after rESW treatment, we choose to single-cell clone which culture cells at a density of 1/well in a 96-well plate. The cloned cells were then subjected to immunofluorescence staining (Detailed protocols are provided in Supplementary Methods).

2.10. Statistical analysis

Quantitative data were presented as mean ± standard deviation (SD). GraphPad Prism 8 (GraphPad, La Jolla, CA, USA) software was used for statistical analysis. Student's t-test (two-tailed), one-way ANOVA or two-way ANOVA was employed to evaluate all statistical analyses. Differences were considered statistically significant when $P < 0.05$.

3. Results

3.1. rESW promotes the proliferation of NSCs

To clarify the optimal dose of rESW that affects NSCs proliferation, firstly, we used Cell Counting Kit-8 (CCK 8) to detect the effect of different rESW excitation pressure on NSCs. Compared with the control group, rESW at a dose of 1.5 bar, 500 points, and 2 Hz significantly increased the number of NSCs 72 h after rESW treatment (Fig. 2A–D and Supp 1). Between 1.2 bar and 1.5 bar, the proliferation-promoting effect of rESW on NSCs was positively correlated with the dose. Interestingly, when the dose was over 1.5 bar, the opposite effect was observed, and the Western Blot experiment confirmed the observation (Fig. 2B and C). Therefore, the dose we used in this study was 1.5 bar, 500 points, 2 Hz. At the same time, at 72 h, we used RT-

qPCR to detect the expression of NSCs specific protein Nestin mRNA and used 5-Bromodeoxyuridine (BrdU) labeling method to detect cell proliferation. We observed that compared with the control group, the excitation pressure of 1.5 bar can significantly promote the proliferation of NSCs, showed by the number of BrdU+/nestin + positive cells, which were increased significantly (Fig. 2E and F). In addition, to clarify more clearly that rESW can promote the self-renewal of NSCs, we performed single-cell cloning experiments, which showed that 72 h after rESW treatment, NSCs still expressed the NSC-specific protein Nestin (Supp 1).

3.2. rESW inhibits the expression of lncRNA NEAT1 and let 7 b

In order to determine how rESW affects the expression of NEAT1 and let 7 b, we used RT-qPCR to detect the expression of NEAT1 and let 7 b within 72 h after rESW treatment on NSC. It was found that rESW had the most significant inhibitory effect on the expression of NEAT1 at 48 h after the treatment on NSC of rESW. Similarly, the expression of let 7 b was the lowest at 48 h after treatment (Fig. 3A and B). The expression of Nestin mRNA was highest at 48 h after the treatment (Fig. 3C). Interestingly, we used CCK 8 to detect the proliferation of NSC at 48 h after the treatment of different excitation pressures of rESW and found that 1.5 bar had the most obvious effect on the proliferation of NSC, there was a statistically significant difference between 1.5 bar and 1.6 bar. But there was no statistically significant difference between 1.5 bar and 1.4 bar (Fig. 3D). Thence, we chose to complete our subsequent experiments at 48 h after rESW treatment.

3.3. rESW mediates NSC proliferation through the lncRNA-let 7 b axis

As the self-renewal ability of NSC decreases, let 7 b expression increases. In a study with the proliferation of liver cancer cells, Liu Q et al. used the dual luciferase reporter gene experiment to show that there was an interaction between NEAT1 and let 7 b [10]. Therefore,

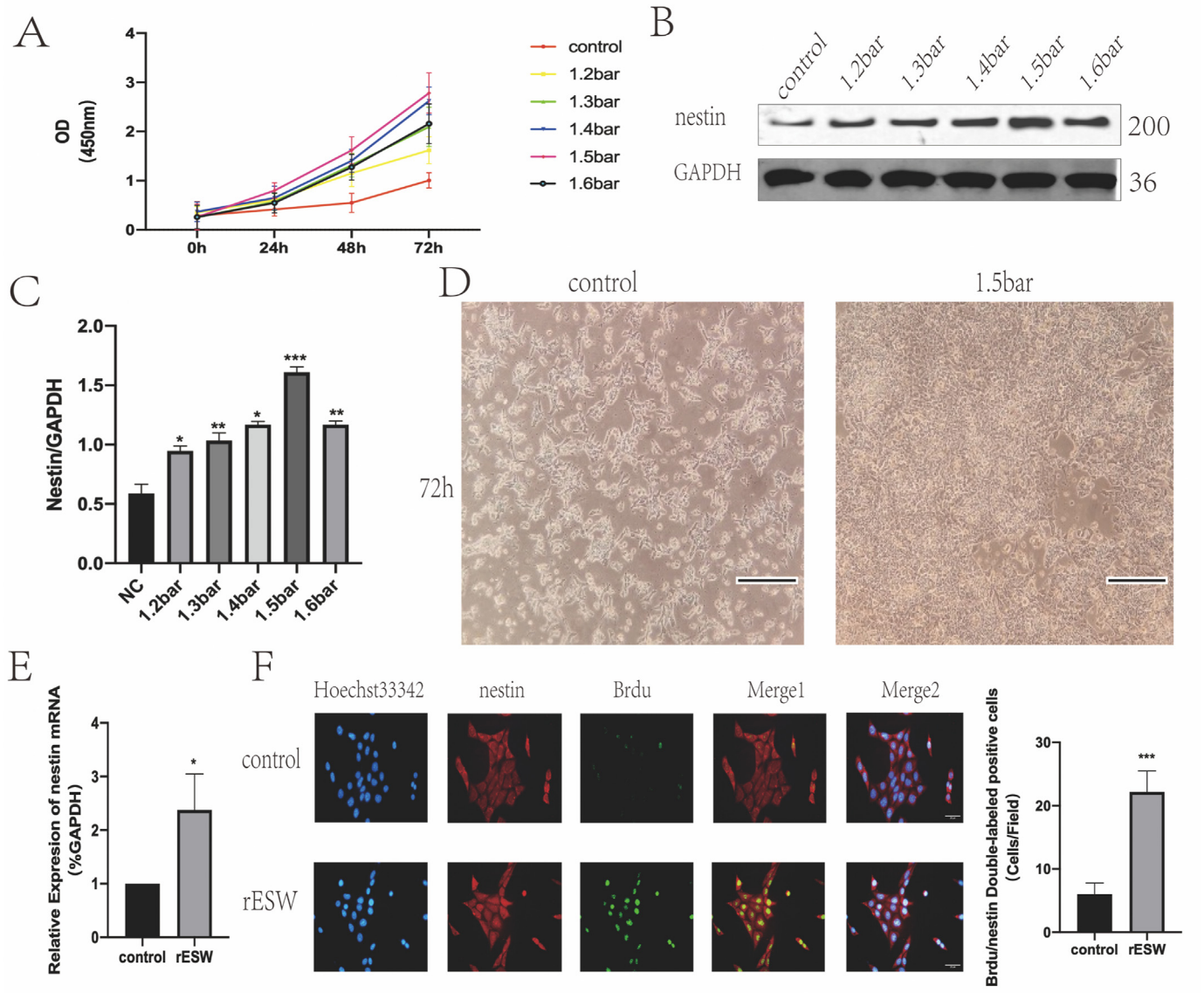

Fig. 2. (A) CCK8 results showed the optimal excitation pressure of rESW to promote the proliferation of NSCs ($p < 0.05$ by two-way ANOVA) (B) , (C) The chart GAPDH of Western Blot demonstrates Nestin expression 72 h after rESW treatment. The data shown in (C) were analyzed by one-way ANOVA*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ (D) The microscopic pictures show the number of NSCs at 72 h in the 1.5 bar treatment group is significantly more than that in the control group , Bar = 100 μm (E) The chat graph of RT-qPCR results demonstrates the Nestin mRNA expression 72 h after 1.5 bar rESW treatment (F) The immunostaining of NSCs demonstrates the proliferation changes 72 h after rESW treatment, with cell proliferation marker BrdU and NSCs marker Nestin. Bar = 20μm. *$p < 0.05$, ***$p < 0.001$ by Student's t-test.

we wanted to know whether the NEAT1-let 7 b axis regulates NSC proliferation.

We overexpressed the NEAT1 in NSC by transfecting plasmid into the NSC (Fig. 4A) and found that rESW mediates NSCs proliferation through the NEAT1 (Fig. 4G). RT-qPCR and Western blot were used to detect the expression of Nestin mRNA and relative protein, and the results obtained were consistent with the results of CCK 8 (Fig. 4B, E). Furthermore, by using BrdU to display NSCs proliferation, we found the number of BrdU+/Nestin + positive cells were increased significantly, and the results were consistent with that of CCK 8 (Fig. 5A).

At the same time, we overexpressed let 7 b by transfecting let 7 b mimics into the NSC (Fig. 4C). We found that rESW mediates NSCs proliferation through the let 7 b (Fig. 4H). The results from RT-qPCR and Western blot were consistent with that of CCK8 (Fig. 4D, F), so did that of BrdU (Fig. 5B).

Interestingly, when we overexpressed NEAT1, the expression of let 7 b was increased. But overexpression of let 7 b did not change the expression of NEAT1 (Fig. 4I and J).

3.4. Let 7 b regulates the proliferation of NSCs by promoting the expression of P21

As a member of the tumor suppressor gene family, P21 can regulate cell senescence, self-renewal, etc. Recently, it has been widely reported in research centered on NSCs proliferation. Hui L et al. have predicted and verified that let 7 b and P21 can bind to each other in liver cells by using a dual luciferase reporter gene experiment [20]. Therefore, we speculate that let 7 b and P21 can interact with each other to affect NSCs proliferation.

We observed an increase in the expression of P21 by overexpression of let 7 b in NSCs. At the same time, we detected the expression of Cyclin D1 and found that the expression of let 7 b was negatively correlated with the expression of Cyclin D1. Moreover, rESW can rescue the increase in P21 expression and the decrease in Cyclin D1 expression caused by let 7 b overexpression (Fig. 6A–E).

4. Discussion

The recovery of the CNS is very slow after injury, and it is not easy to regenerate. The patient feels painful and causes great distress to their quality of life. After the cerebrovascular accident, even if the systemic thrombolytic treatment within 4.5 h at the first time, 2/3 of the patients still have neurological dysfunction and disability [23]. Therefore, promoting the repair of the central nervous system after injury is the current research focus on neurology and rehabilitation medicine. In recent years, because NSCs are able to promote repair after brain injury, increasing studies have focused on NSCs, providing new treatment ideas for repair after TBI. The

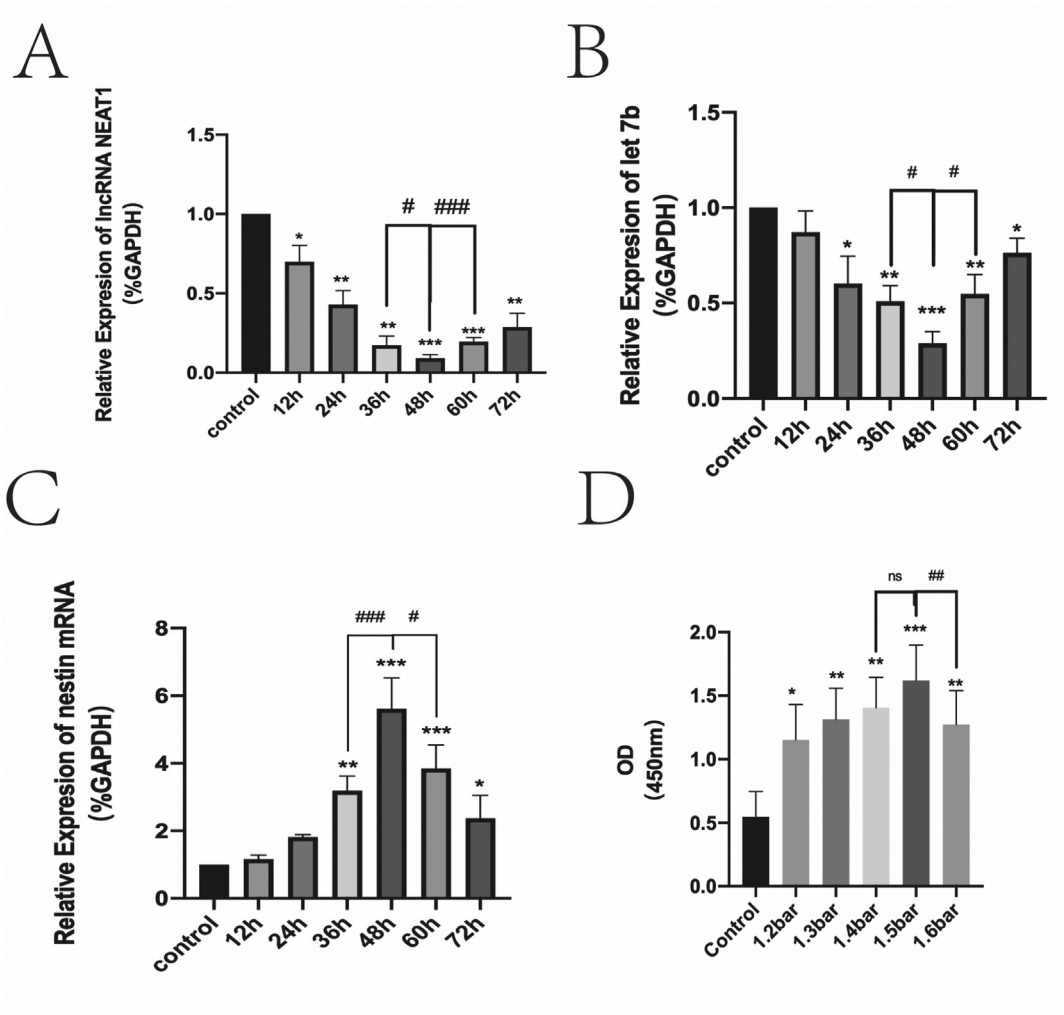

Fig. 3. Relative expression of NEAT1(A), let 7 b (B) and nestin (C) within 72 h after rESW treatment in NSCs (D) The effect of different excitation pressures on the proliferation of NSCs at 48 h after rESW treatment. The data are shown as the mean ± SD *p < 0.05, **p < 0.01, ***p < 0.001.

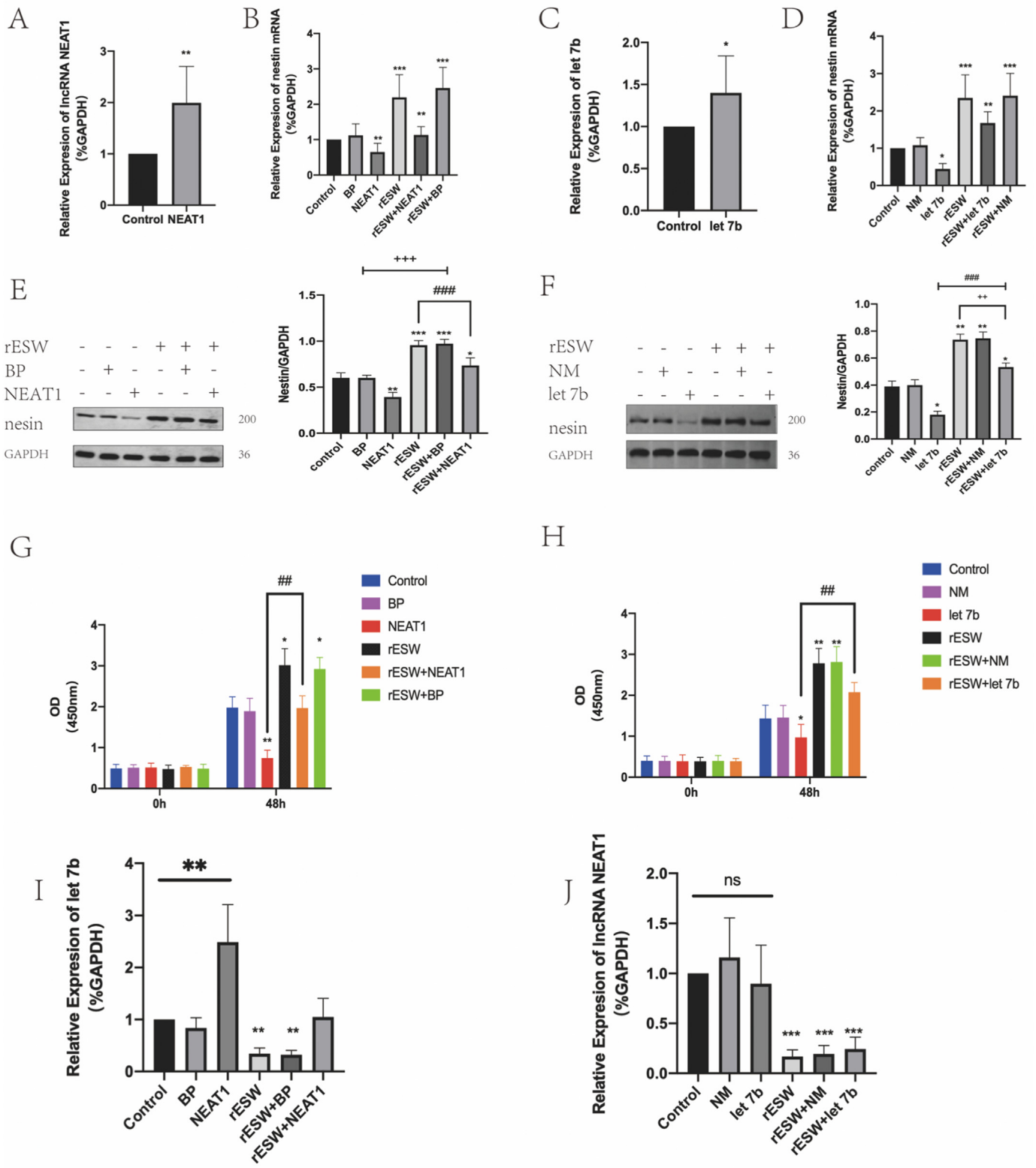

Fig. 4. (A) The RT-qPCR results demonstrate the transfection efficiency of NEAT1 overexpression in NSCs (C) The RT-qPCR results demonstrate the transfection efficiency of let 7 b overexpression. (B, E, G) Results of RT-qPCR and Western Blot show that NEAT1 overexpression inhibits the expression of Nestin gene and protein. CCK 8 results show the effect of NEAT1 overexpression on NSCs proliferation. Treatment with rESW rescues the reduction. Similar effects are observed in NSCs overexpressing let 7 b (D, F, H) (I–J) The results demonstrate the effect of NEAT1 and let 7 b overexpression on each other. The data are shown as the mean ± SD *p < 0.05, **p < 0.01, ***p < 0.001.

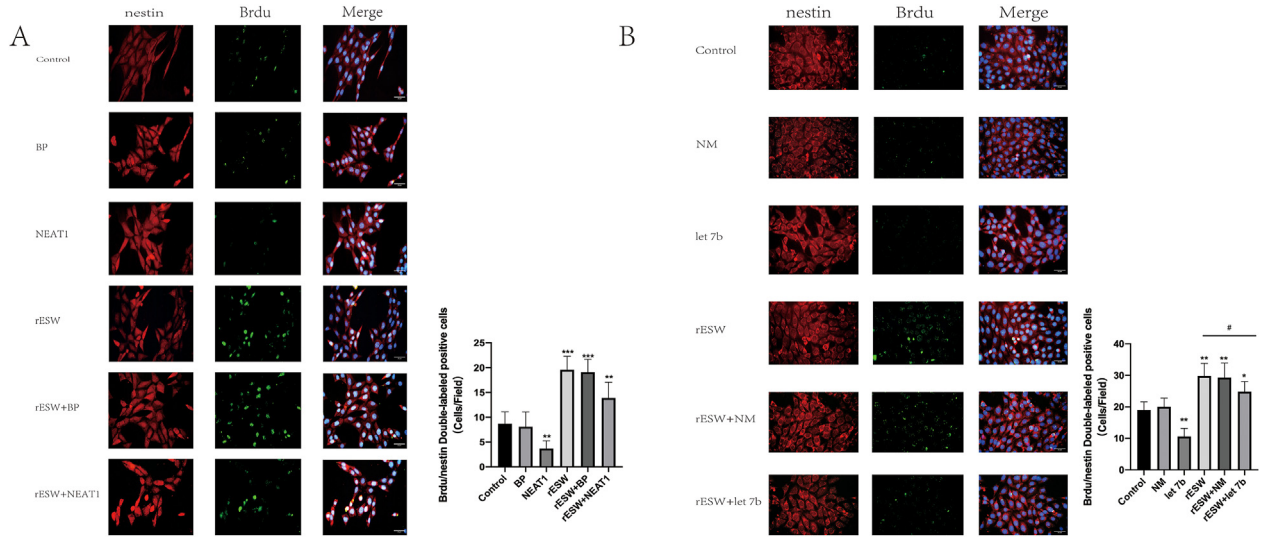

Fig. 5. (A–B) The immunostaining results demonstrate the inhibitory effect of NEAT1 or let 7 b overexpression on proliferation of NSCs, which is reversed by rESW treatment, Bar = 20 μm. The data are shown as the mean ± SD *p < 0.05, **p < 0.01, ***p < 0.001.

increasing evidence indicates the existing of post-injury cell proliferation in SVZ [24,25] and SGZ [26]; where the NSCs originate. However, the time window for NSCs proliferation is narrow, and aging reduces SVZ cell proliferation and migration of neuroblasts after injury, even though neurogenesis is still observed [27]. As a non-invasive treatment, rESW has been proven to promote the proliferation of bone stem cells. In the current study with rESW, we found that low energy rESW (1.5 bar, 2 Hz, 500 points) not only does not cause cell damage, but also promotes the proliferation of NSCs, which brings new ideas to the limited repair of CNS after injury (Fig. 2 and Supp 1).

After treatment by rESW 72 h, the single-cell cloning NSC could also express Nestin, the specific protein the NSCs express. That is to say, rESW could promote the self-renew of NSCs (Supp 1).

At present, the cognition of NEAT1 is mainly focused on its regulation of the progress of cancer cells, and little is known about whether it affects the development of the central nervous system. Interestingly, we found that rESW could promote the proliferation

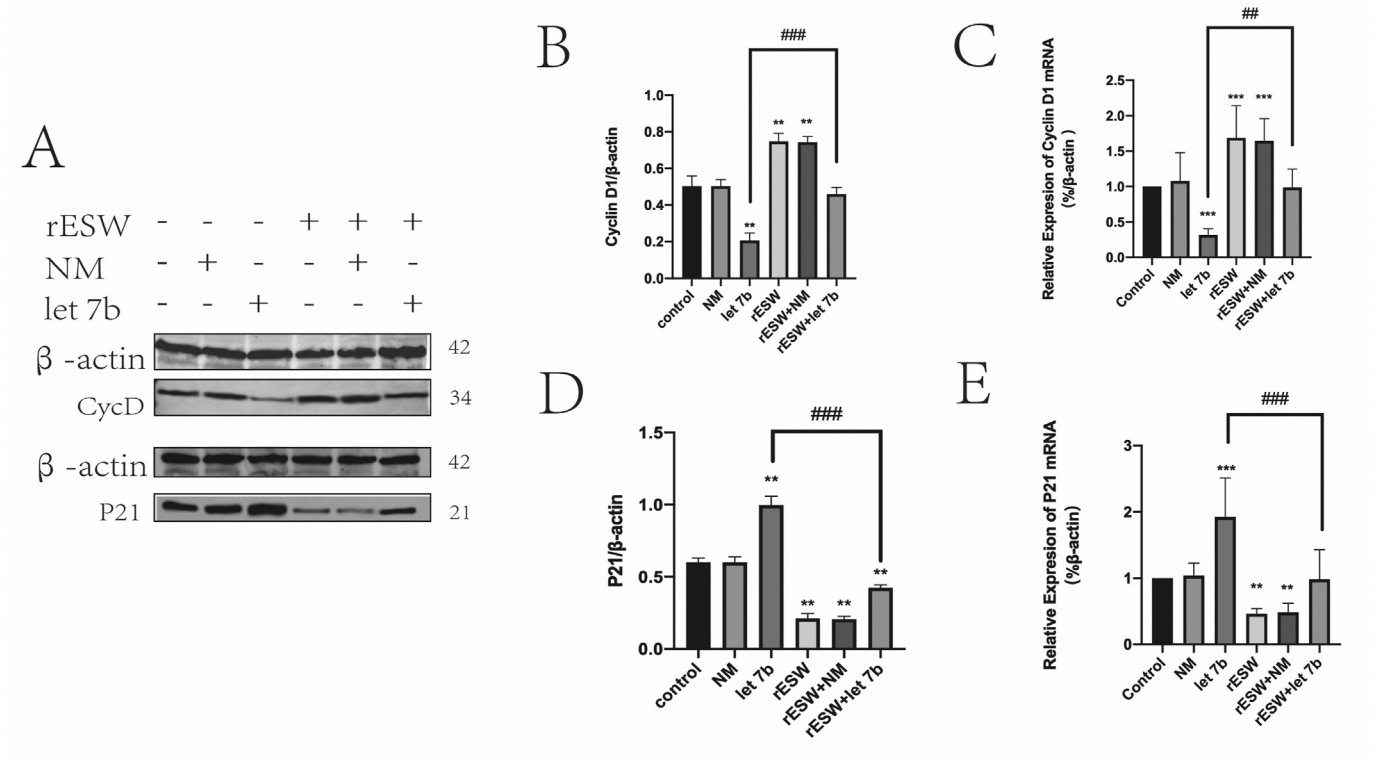

Fig. 6. Let 7 b inhibits the expression of Cyclin D1 (A, B, Western Blot) (C, RT-qPCR), and promotes the expression of P21 (A, D, Western Blot) (E, RT-qPCR). Treatment with rESW rescues the reduction. The data are shown as the mean ± SD *p < 0.05, **p < 0.01, ***p < 0.001.

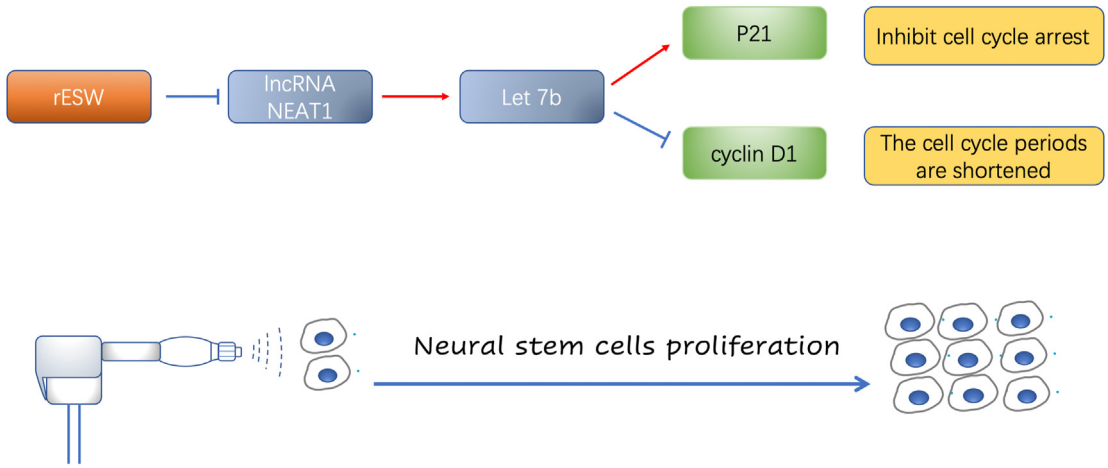

Fig. 7. Let 7 b mediates the regulation of the expression of Cyclin D1 and P21 caused by lncRNA NEAT1, and then regulating the proliferation of NSCs. rESW can regulate NSCs proliferation through NEAT1-let 7 b-P21 axis.

of NSCs inhibited by the expression of NEAT1. Our results were also in line with previous studies. Cui Y et al. found that the overexpression of NEAT1 in spinal cord neural progenitor cells (SC—NPCs) can cause SC-NPC to differentiate like neurons and inhibit apoptosis after spinal cord injury [28]. On the contrary, the loss of NEAT1 will reduce the differentiation and migration of neurons. Let-7 family continuously and dynamically express during neurogenesis with various functions [29]. Our further exploration found that let 7 b is the downstream target of NEAT1 to inhibit the proliferation of NSCs. rESW could regulate NSCs proliferation through inhibiting NEAT1-let 7 b axis. Thus, our results also indicated that NEAT1 may have some connections in regulating cell behavior under pathological and physiological conditions.

miRNA is thought to regulate the proliferation of stem cells to ensure proper cell fate transition [30]. As an important molecule that regulates the proliferation of NSCs, P21 can arrest the cell cycle and can also achieve the effect of inhibiting the proliferation of NSCs [31,32]. We therefore hypothesized that let 7 b might mediate NSCs proliferation through P21. In our research, we proved that let 7 b not only inhibits the expression of Cyclin D1, but also promotes the expression of P21, enriching the mechanism of let 7 b inhibiting the proliferation of NSCs. In other words, our study identified P21 as a key target of let-7b in NSCs. Therefore, we concluded that let 7 b can inhibit the proliferation of NSCs not only because it can inhibit the expression of Cyclin D1 to prolong the cell cycle, but partly because it can promote the expression of P21 to arrest the cell cycle. These studies, including ours, suggest that let-7b plays a role in NSC proliferation across a spectrum of developmental stages through targeting distinct key molecules. We can rescue the reduction of NSCs proliferation because of the overexpression of let 7 b by low energy rESW.

However, our research currently has some limitations. How rESW, as an exogenous mechanical signal, was transformed into an endogenous chemical signal should be clearly verified. And the specific mechanism of excitement of cells caused by rESW should be explored. Meanwhile, the NSCs were cultured *in vitro*, which may not represent the *in vivo* status. Moreover, the mechanisms of *in vivo* experiments still need further exploration and validation.

There is no doubt that, however, rESW as a non-invasive and safe therapy can effectively activate NSCs compared to other treatments. It is certain that rESW as an innovative treatment for CNS injuries has far-reaching translational prospects. It continues to stimulate scientists and clinicians to explore specific mechanisms and provide a theoretical basis for future clinical applications. In addition, our results further verify the critical role of radial shockwave energy on biological effects, and the results provide a reference for clinical therapy.

5. Conclusion

In the present study, we demonstrated that radial shockwave is capable of enhancing the self-renewal capacity of NSC *in vitro*, and we screened out the optimized parameters in our experimental system. Moreover, we identified that the activation of NEAT1-let 7 b-P21 axis contributed to this promising effect mediated by radial shockwave (Fig. 7).

Ethics approval and consent to participate

Not Applicable.

Consent for publication

All of the authors have given their consent for publication.

Availability of data and materials

None.

Funding

This work was supported by the National Natural Science Foundation of China (81871840) and Shenyang Science and technology plan population and health special project (19-112-4-064).

Authors' contributions

KH and NK have substantial contributions to the conception and design; acquisition, analysis, and interpretation of the data; and manuscript writing. NK, JL and YWM contributed to the analysis and interpretation of the data and manuscript writing. KH and JL has substantial contributions to the cell culture. YWM, XTY and JL have substantial contributions to the conception and design, financial support, and analysis and interpretation of the data. All authors read and approved the final manuscript.

Availability of data and materials

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

Authors' information

Kun Han, Department of Rehabilitation Medicine, The First Hospital of China Medical University, Shenyang, Liaoning, P.R. China.

Nan Kang, Department of Rehabilitation Medicine, The First Hospital of China Medical University, Shenyang, Liaoning, P.R. China.

Xiaotong Yu, Institute of Meta-Synthesis Medicine, Beijing, P.R. China.

Jie Lu, Department of Human Anatomy, College of Basic Medical Sciences, China Medical University, Shenyang, Liaoning, P.R. China.

Yuewen Ma, Department of Rehabilitation Medicine, The First Hospital of China Medical University, Shenyang, Liaoning, P.R. China.

Declaration of competing interest

The authors declare that they have no competing interests.

Acknowledgements

We thank Xiaotong Yu for assistance with the radial shock wave instrument.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.reth.2022.06.006.

References

[1] Arvidsson A, Collin T, Kirik D, Kokaia Z, Lindvall O. Neuronal replacement from endogenous precursors in the adult brain after stroke. Nat Med 2002;8:963–70.
[2] Azad TD, Veeravagu A, Steinberg GK. Neurorestoration after stroke. Neurosurg Focus 2016;40:E2.
[3] Cui Y, Yin Y, Xiao Z, Zhao Y, Chen B, Yang B, et al. LncRNA Neat1 mediates miR-124-induced activation of Wnt/β-catenin signaling in spinal cord neural progenitor cells. Stem Cell Res Ther 2019;10:400.
[4] De Gioia R, Biella F, Citterio G, Rizzo F, Abati E, Nizzardo M, et al. Neural Stem Cell Transplantation for Neurodegenerative Diseases. Int J Mol Sci 2020;21.
[5] Han D, Li J, Wang H, Su X, Hou J, Gu Y, et al. Circular RNA circMTO1 acts as the sponge of microRNA-9 to suppress hepatocellular carcinoma progression. Hepatology 2017;66:1151–64.
[6] He Y, Liu X, Chen Z. Glial Scar-a Promising Target for Improving Outcomes After CNS Injury. J Mol Neurosci 2020;70:340–52.
[7] Hsiao C-C, Huang W-H, Cheng K-H, Lee C-T. Low-Energy Extracorporeal Shock Wave Therapy Ameliorates Kidney Function in Diabetic Nephropathy. Oxid Med Cell Longev 2019. 8259645.
[8] Hsu C-C, Cheng J-H, Wang C-J, Ko J-Y, Hsu S-L, Hsu T-C. Shockwave Therapy Combined with Autologous Adipose-Derived Mesenchymal Stem Cells Is Better than with Human Umbilical Cord Wharton's Jelly-Derived Mesenchymal Stem Cells on Knee Osteoarthritis. Int J Mol Sci 2020;21.
[9] Huang L, Zhang L. Neural stem cell therapies and hypoxic-ischemic brain injury. Progress in neurobiology 2019;173.
[10] Hui L, Zheng F, Bo Y, Sen-Lin M, Ai-Jun L, Wei-Ping Z, et al. MicroRNA let-7b inhibits cell proliferation via upregulation of p21 in hepatocellular carcinoma. Cell Biosci 2020;10:83.
[11] Jin K, Minami M, Lan JQ, Mao XO, Batteur S, Simon RP, et al. Neurogenesis in dentate subgranular zone and rostral subventricular zone after focal cerebral ischemia in the rat. Proc Natl Acad Sci U S A 2001;98:4710–5.
[12] Kang N, Yu X, Ma Y. Radial extracorporeal shock wave therapy in a patient with decubitus ulcer after spinal cord injury: a case report. Am J Transl Res 2020;12:2093–8.
[13] Kobayashi M, Chijimatsu R, Yoshikawa H, Yoshida K. Extracorporeal shock wave therapy accelerates endochondral ossification and fracture healing in a rat femur delayed-union model. Biochem Biophys Res Commun 2020;530:632–7.
[14] Liu Q, Shi H, Yang J, Jiang N. Long Non-Coding RNA NEAT1 Promoted Hepatocellular Carcinoma Cell Proliferation and Reduced Apoptosis Through the Regulation of Let-7b-IGF-1R Axis. Onco Targets Ther 2019;12:10401–13.
[15] Mello SS, Sinow C, Raj N, Mazur PK, Bieging-Rolett K, Broz DK, et al. is a p53-inducible lincRNA essential for transformation suppression. Genes Dev 2017;31:1095–108.
[16] Moraga A, Pradillo JM, García-Culebras A, Palma-Tortosa S, Ballesteros I, Hernández-Jiménez M, Moro MA, et al. Aging increases microglial proliferation, delays cell migration, and decreases cortical neurogenesis after focal cerebral ischemia. J Neuroinflammation 2015;12:87.
[17] Parent JM, Vexler ZS, Gong C, Derugin N, Ferriero DM. Rat forebrain neurogenesis and striatal neuron replacement after focal stroke. Ann Neurol 2002;52:802–13.
[18] Patties I, Kallendrusch S, Böhme L, Kendzia E, Oppermann H, Gaunitz F, et al. The Chk1 inhibitor SAR-020106 sensitizes human glioblastoma cells to irradiation, to temozolomide, and to decitabine treatment. J Exp Clin Cancer Res 2019;38:420.
[19] Qian C, Dong B, Wang X-Y, Zhou F-Q. In vivo glial trans-differentiation for neuronal replacement and functional recovery in central nervous system. FEBS J 2021;288:4773–85.
[20] Rackov G, Iegiani G, Uribe D, Quezada C, Belda-Iniesta C, Escobedo-Lucea C, et al. Potential Therapeutic Effects of the Neural Stem Cell-Targeting Antibody Nilo1 in Patient-Derived Glioblastoma Stem Cells. Front Oncol 2020;10:1665.
[21] Ramesh S, Zaman F, Madhuri V, Sävendahl L. Radial Extracorporeal Shock Wave Treatment Promotes Bone Growth and Chondrogenesis in Cultured Fetal Rat Metatarsal Bones. Clin Orthop Relat Res 2020;478:668–78.
[22] Romero-Ramírez L, Nieto-Sampedro M, Barreda-Manso MA. Integrated Stress Response as a Therapeutic Target for CNS Injuries. Biomed Res Int 2017.6953156.
[23] Russo MV, McGavern DB. Inflammatory neuroprotection following traumatic brain injury. Science 2016;353:783–5.
[24] Shi Y, Sun G, Zhao C, Stewart R. Neural stem cell self-renewal. Crit Rev Oncol Hematol 2008;65:43–53.
[25] Sun G, Alzayady K, Stewart R, Ye P, Yang S, Li W, et al. Histone demethylase LSD1 regulates neural stem cell proliferation. Mol Cell Biol 2010;30:1997–2005.
[26] Vieira MS, Santos AK, Vasconcellos R, Goulart VAM, Parreira RC, Kihara AH, et al. Neural stem cell differentiation into mature neurons: Mechanisms of regulation and biotechnological applications. Biotechnol Adv 2018;36:1946–70.
[27] Yagita Y, Kitagawa K, Ohtsuki T, Takasawa K, Miyata T, Okano H, et al. Neurogenesis by progenitor cells in the ischemic adult rat hippocampus. Stroke 2001;32:1890–6.
[28] Yao M-J, Chen G, Zhao P-P, Lu M-H, Jian J, Liu M-F, et al. Transcriptome analysis of microRNAs in developing cerebral cortex of rat. BMC Genomics 2012;13:232.
[29] Zhang J, Jiao J. Molecular Biomarkers for Embryonic and Adult Neural Stem Cell and Neurogenesis. Biomed Res Int 2015;2015:727542.
[30] Zhang J, Kang N, Yu X, Ma Y, Pang X. Radial Extracorporeal Shock Wave Therapy Enhances the Proliferation and Differentiation of Neural Stem Cells by Notch, PI3K/AKT, and Wnt/β-catenin Signaling. Sci Rep 2017;7:15321.
[31] Zhang Y, Chen B, Li D, Zhou X, Chen Z. LncRNA NEAT1/miR-29b-3p/BMP1 axis promotes osteogenic differentiation in human bone marrow-derived mesenchymal stem cells. Pathol Res Pract 2019;215:525–31.
[32] Zhao C, Sun G, Li S, Lang M-F, Yang S, Li W, et al. MicroRNA let-7b regulates neural stem cell proliferation and differentiation by targeting nuclear receptor TLX signaling. Proc Natl Acad Sci U S A 2010;107:1876–81.