Uncarboxylated osteocalcin promotes osteogenesis and inhibits adipogenesis of mouse bone marrow-derived mesenchymal stem cells via the PKA-AMPK-SIRT1 axis

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Received September 18, 2020; Accepted April 27, 2021

DOI: 10.3892/etm.2021.10312

Abstract. Osteoporosis is a bone disease characterized by reduced bone density, thin cortical bone and large gaps in the bone's honeycomb structure, which increases the risk of bone fragility. Uncarboxylated osteocalcin (unOC), a vitamin K-dependent bone protein, is known to regulate carbohydrate and energy metabolism. A previous study demonstrated that unOC promotes the differentiation of mouse bone marrow-derived mesenchymal stem cells (BMSCs) into osteoblasts, but inhibits their differentiation into adipocytes. However, the underlying mechanism remains unknown. The present study showed that unOC regulated the differentiation potential of BMSCs via protein kinase A (PKA)/AMP-activated protein kinase (AMPK)/sirtuin 1 (SIRT1) signaling. SIRT1, a member of the sirtuin family with deacetylation functions, was upregulated by unOC in BMSCs. Transfection analyses with SIRT1 small interfering RNA indicated that the unOC-induced differentiation shift in BMSCs required SIRT1. Examination of SIRT1 downstream targets revealed that unOC regulated the acetylation levels of runt-related transcription factor (RUNX) 2 and peroxisome proliferator-activated receptor γ (PPARγ). Therefore, unOC inhibited adipogenic differentiation by PPARγ acetylation and promoted osteogenic differentiation by RUNX2 deacetylation. Moreover, phosphorylated PKA and AMPK protein levels increased after unOC treatment, which led to the upregulation of SIRT1. Western blot analysis with PKA and AMPK inhibitors indicated that the PKA-AMPK signaling pathway functioned upstream of SIRT1 and positively regulated SIRT1 expression. These findings led us to propose a model in which unOC regulated BMSC osteogenic differentiation through the PKA-AMPK-SIRT1 axis, giving evidence towards the therapeutic potential of unOC in osteoporosis treatment.

Introduction

Osteoporosis is a bone disease characterized by decreased bone mass, bone microstructure degeneration or destruction and an increased fracture rate (1). Bone marrow-derived mesenchymal stem cells (BMSCs) can differentiate into a variety of cells, such as adipocytes, chondrocytes and nerve cells. However, their differentiation into cell types other than osteoblasts may lead to a decrease in the number of bone cells, eventually resulting in osteoporosis (2). Previous studies have shown that exogenous mesenchymal stem cell (MSC) transplantation can restore the impaired function of BMSCs, thereby promoting osteoblast formation and increasing bone regeneration (3,4). Mo et al (5) also reported that a compound extracted from Phyllanthus amarus promotes the osteogenic differentiation of BMSCs and increases bone mass by activating the Wnt/β-catenin signaling pathway. In addition, Luo et al (6) found that runt-related transcription factor (RUNX) 1 regulates the osteogenic differentiation of BMSCs by inhibiting adipogenesis-related pathways. Therefore, BMSCs are beneficial for osteoblast regeneration and bone remodeling, and are expected to be utilized for the treatment of bone-related diseases such as osteoporosis and osteoarthritis (7).

Factors that affect the differentiation of BMSCs include physical (cell shape and external mechanical forces), chemical (dexamethasone and insulin are required for adipogenic differentiation), biological (mineral deposition and cell proliferation) and age (senescence) (8,9). Osteocalcin is a vitamin K-dependent bone protein that is synthesized in the human body by osteoblasts (10). In particular, γ-glutamate

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Abbreviations: unOC, uncarboxylated osteocalcin; BMSCs, bone marrow-derived mesenchymal stem cells; sFRP, secreted frizzled-related protein; ALP, alkaline phosphatase; SIRT1, sirtuin 1; RT-qPCR, reverse transcription-quantitative PCR; Osx, osterix; RUNX, runt-related transcription factor; Fabp4, fatty acid-binding protein 4; PPARγ, peroxisome proliferator-activated receptor γ; PKA, protein kinase A; AMPK, AMP-activated protein kinase; NAD, nicotinamide adenine dinucleotide; LKB1, liver kinase B1; α-MEM, α-minimal essential medium; FAS, fatty acid synthase; siRNA, small interfering RNA; ODI, osteogenic differentiation inducers; TBST, Tris-buffered saline with Tween 20; C/EBPα, CCAAT-enhancer-binding protein α; NG, normal group; NC, negative control

Key words: uncarboxylated osteocalcin, bone marrow-derived mesenchymal stem cells, osteogenic differentiation, sirtuin 1, signaling pathway
carboxylase can catalyze the carboxylation of three glutamate residues at positions 17, 21, and 24 in the molecular structure of osteocalcin (11). According to whether these three sites are fully carboxylated, osteocalcin can be divided into two subtypes: γ-Carboxyl osteocalcin and incomplete carboxylated/uncarboxylated osteocalcin (unOC) (11). Previous studies have shown that osteocalcin-knockout in mice can affect bone mineralization (12,13). Therefore, osteocalcin is hypothesized to affect osteoblast and osteoclast activity to regulate mineralization (14,15). A previous study indicated that unOC can promote the differentiation of BMSCs into osteoblasts (16). However, further study is required to identify the specific mechanism by which unOC regulates the osteogenic differentiation of MSCs.

Studies have shown that sirtuin 1 (SIRT1) is associated with the differentiation of MSCs (17,18). SIRT1 is a nicotinamide adenine dinucleotide (NAD⁺)-dependent lysine deacetylase. It activates the Wnt signaling pathway and promotes MSC osteogenic differentiation by the deacetylation of secreted frizzled-related protein 1 (sFRP1), sFRP2 and disheveled-binding antagonist of β catenin 1 (19,20). SIRT1 positively regulates RUNX2, a key transcription factor associated with osteoblasts, to activate the transcription of BMSC osteogenic differentiation (21). SIRT1 can also deacetylate peroxisome proliferator-activated receptor γ (PPARγ), inhibiting PPARγ activity and attenuating lipogenesis to enhance osteogenic differentiation (22). Therefore, it was hypothesized that unOC can promote the differentiation of BMSCs through SIRT1, thereby promoting osteogenic formation.

5'-AMP-activated protein kinase (AMPK) is a protein kinase closely associated with glucose metabolism (23). Increasing evidence suggests that SIRT1 and AMPK can interact to regulate the osteogenic and adipogenic differentiation of MSCs (24). AMPK can increase SIRT1 activity by promoting NAD⁺ biosynthesis, where SIRT1 can also upregulate AMPK activity through the liver kinase B1 (LKB1)-AMPK axis (25). A previous study reported that protein kinase A (PKA) regulates SIRT1 expression by activating serine/threonine kinase LKB1 (26). Based on these studies, it was hypothesized that unOC regulated BMSC differentiation into osteoblasts via the PKA-AMPK-SIRT1 axis.

The present study aimed to further explore the mechanism and the signaling pathways associated with the promotion of BMSC osteogenic differentiation by unOC and to uncover novel avenues for the treatment of osteoporosis.

Materials and methods

Preparation of unOC. unOC was prepared as previously described by Liu and Yang (16) with slight modifications. The method used to lyse the bacteria in the present study was to freeze the bacteria at -80°C before using an ultrasonic cell disruptor. In brief, the plasmid pet30a (cat no. JX210976.1 GI:392880915; Biovector Science Lab, Inc.; http://www.biovector.net/product/1040481.html) containing the mouse unOC recombinant gene was previously constructed in the laboratory (27). It was made by amplifying the mouse osteocalcin gene (accession no. NM_007541) sequences by PCR based on NCBI database (The source of the template: Mouse bone tissue), cloning into the pet-30a vector to obtain the pet-30a-OC recombinant plasmid. It was introduced into Escherichia coli, and bacteria populations containing the plasmid vector with a resistance gene were selected with kanamycin antibiotic (1:1,000; cat. no. K1010; Beijing Lablead Biotechnology Co., Ltd.). The selected populations were cultured in liquid phase to the log phase at 37°C for 8 h and induced to express recombinant osteocalcin with 1 mM isopropyl β-d-1-thiogalactopyranoside at 28.5°C for 3 h. Protein (mouse unOC with a six-histidine tag) extraction and purification processes were performed in accordance with the previous description (28). The obtained osteocalcin was isolated, purified by binding to a recombinant protein in a Ni Sepharose™ 6 Fast Flow column (cat. no. 17531801; Cytiva), and eluted with 150 mM of imidazole (cat. no. 110070; Beijing Solarbio Science & Technology Co., Ltd.). The purified protein was dialyzed and concentrated. The molecular weight of the protein was determined using 10% SDS-PAGE (the amount of protein loaded per lane: 20 μg) and Coomassie blue staining (Coomassie Blue Fast Staining Solution; cat. no. P0017; Beyotime Institute of Biotechnology) was used. Experimental conditions for Coomassie staining: 50 ml deionized water was added to the protein gel and heated at 100°C for 3 min, before being shaken on a horizontal shaker at 37°C for 5 min. The gels were then incubated in ~20 ml Coomassie Blue Fast Staining Solution at 100°C for 3 min and incubated on a shaker at a temperature of 37°C to decolorize. Protein bands were observed at room temperature after 2 h. Western blot analysis was used for protein detection.

Cell culture and differentiation. In total, 12 4-week-old male C57BL/6 mice (certificate no. SCXK 2016-0006) were purchased from Charles River Laboratories, Inc. During the research process, all animal experiments were conducted in accordance with the standards in University of Chinese Academy of Sciences Institutional Committee for the Use and Care of Animals. The mice (weight range, 16-18 g) were used for each experiment. Housing conditions are 25°C, relative air humidity: 50-60%. Mice had free access to food and water and were on a 12-h light/dark cycle. All experimental protocols for the present study were approved by The Institutional Animal Care and Use Committee of the University of Chinese Academy of Sciences (Beijing, China). Isolation and culture of mouse BMSCs were performed as described previously by Cai et al (29). Briefly, mice were sacrificed through cervical dislocation, the tibia and femur were separated and the surrounding muscle tissue was removed. The removed bone tissue was placed in PBS with 100 U/ml penicillin and 100 mg/l streptomycin (the double antibody, and both ends of the plasmid vector with a resistance gene were selected and bacteria populations containing the plasmid vector with a resistance gene were selected with kanamycin antibiotic (1:1,000; cat. no. K1010; Beijing Lablead Biotechnology Co., Ltd.). The collected media were centrifuged at 278 x g for 10 min at 37°C, resuspended in α-MEM supplemented with 10% FBS (cat. no. S601P-500; Sera Pro), 100 U/ml penicillin and 100 mg/l streptomycin. Cells were incubated at 37°C in 5% CO₂ for 72 h, and half of the growing medium was replaced every 12 h. Fresh medium was added and was replaced every 2 days thereafter. BMSCs were then expanded for a maximum of four passages, trypsinized and seeded at a density of ~1x10⁶ cells per well in six-well
BMSCs were passaged to the third generation and 60‑80% of the adherent cells were confluent. Small interfering RNA (siRNA) targeting SIRT1 (forward 5'-CCCUCAGCGCAUUUUUGATT-3' and reverse 5'-AUCAAGAGGCCUUGAGGTT-3') and negative control (NC; forward 5'-UCUGACAGGUGACUGUTT-3' and reverse 5'-ACUGAAGCAGUGUGAGATT-3') siRNA were purchased from JTS Scientific (30). The overall transfection procedure was in accordance with the recommendations of the manufacturer. Lipofectamine® 3000 (cat. no. L3000015; Invitrogen; Thermo Fisher Scientific, Inc.) was used to transfect 20 nM of the siRNA and the NC siRNA into the cells at 37°C. The cells were continuously transfected in medium with or without unOC until they were used for experiments. Finally, protein samples or RNA were collected for further experiments. The time interval between transfection and subsequent experiments was 48 h.

RNA preparation and reverse transcription‑quantitative (RT‑qPCR) analysis. Total cellular RNA was extracted using 1 ml TRIzol® reagent (Invitrogen; Thermo Fisher Scientific, Inc.) per 10‑cm plate. Total RNA was reverse transcribed into cDNA using Transcript® One‑Step gDNA Removal and cDNA Synthesis SuperMix (cat. no. A T311‑03; Beijing Transgen Biotech Co., Ltd.) and TransStart® Top Green qPCR SuperMix (+Dye II) for qPCR (cat. no. AQ132‑24; Beijing Transgen Biotech Co., Ltd.). Full temperature protocol for RT: The product after cDNA synthesis was incubated at 42°C for 15 min, and then heated at 85°C for 5 sec to inactivate excess reagents. The thermocycling conditions were 95°C for 5 min, then 40 cycles of 94°C for 30 sec, 56°C for 30 sec and 72°C for 30 sec. Gapdh served as the internal standard. The expression levels of target genes were normalized to the expression of Gapdh mRNA. The following primers were used to determine the expression levels of proteins associated with osteogenic differentiation: Fatty acid‑binding protein 4 (Fabp4) forward 5'-AAGTGGGAGTTGGCCTTG‑3' and reverse 5'-GTCGTC TGCCGGTATTT‑3'; fatty acid synthase (Fas) forward 5'-TCGTTTGCTGCTCACAGTTAAG‑3' and reverse 5'-TCAGGTTGGGATGTTGACAGC‑3'; osterix (Osx) forward 5'-CTAGTTCTATGTCGCCAG‑3' and reverse 5'-TCATCAACATCATCATCGT‑3'; alkaline phosphatase (Alp) forward 5'-CAAGAGCTTCTTCTTGCTGT‑3' and reverse 5'-AGGGGTCTTTGTCGGTGTC‑3'; and Gapdh forward 5'-GGCATGGCTCTCAATGACAA‑3' and reverse 5'-TGTTAGGAGATGCAGTCG‑3'.

Immunoprecipitation. The cell culture medium was aspirated and washed three times with ice-cold 4°C PBS. Afterward, RIPA lysis buffer (cat. no. R0020; Beijing Solarbio Science & Technology Co., Ltd.) was added to lyse the cells. Detection of protein concentration: BCA Protein Assay kit (Beyotime Institute of Biotechnology). A total of 200 µg protein samples and 20 µg protein A+G Agarose beads (cat. no. P2012; Beyotime Institute of Biotechnology) were used. The mixture was shaken slowly at 4°C, then centrifuged at 1,000 x g for 5 min and the supernatant was collected for subsequent immunoprecipitation experiments. In total, 2 µg the primary antibody, including anti‑RUNX2 (cat. no. 12556; Cell Signaling Technology, Inc.), anti‑PPARγ (cat. no. 2443; Cell Signaling Technology, Inc.), anti‑acetylated‑lysine (cat. no. 9441; Cell
Signaling Technology, Inc.) was added and shaken slowly overnight at 4°C. Afterwards, completely resuspended 40 µg Protein A + G Agarose was added and the mixture was slowly shaken at 4°C for 3 h. Centrifuge at 278 x g for 5 min at 4°C for washing. After the last wash, the supernatant was removed, 5X SDS-PAGE electrophoresis loading buffer was added, and the resulting pellet was resuspended and vortexed. The sample was centrifuged to the bottom of the tube by instantaneous high-speed centrifugation. After 5 min incubation in a 100°C water bath, some or all samples were collected for western blotting.

Western blotting. BMSCs were washed three times with ice-cold PBS, and lysed with RIPA (cat. no. R0010; Beijing Solarbio Science & Technology Co., Ltd.) buffer. Lysate was crushed with an ultrasonic cell disruptor and the supernatant was reserved. Conditions used for cell were 300 W sound waves, duration of 3 min with, 3-sec intervals at 0°C. The protein concentrations were determined using a Beyotime BCA Protein Assay kit (Beyotime Institute of Biotechnology). Afterward, 20 µg cell lysate (each electrophoresis lane) was separated using a 10% SDS-PAGE gel and transferred to a PVDF membrane. After blocking with 5% milk at 37°C for 2 h, the membrane was incubated with primary antibodies (1:1,1000) at 4°C for 12 h. The membrane was washed three times using Tris-buffered saline with 0.1% Tween-20 (TBST) on a shaker for 10 min, and then incubated with secondary antibody at 37°C for 1 h. After washing three times with TBST, 10 min each time, bands were detected with Immobilon Western Chemilum HRP Substrate (EMD Millipore). The band's optical density value was quantified using Image Lab Software for PC Version 6.1 (Bio-Rad Laboratories, Inc.). The protein quantity was calculated as the optical density value of the protein measured/the optical density value of an internal reference.

Antibodies used in western blot analysis included the following: Anti-β-actin (cat. no. CPA9066; Cohesion Biosciences, Ltd.), anti-SIRT1 (cat. no. 3931), anti-RUNX2 (cat. no. 12556), anti-PPARγ (cat. no. 2443), anti-CCAAT-enhancer-binding protein alpha (C/EBPα; cat. no. 2295), anti-acetylated-lysine (cat. no. 9441), anti-PKA (cat. no. 4782), anti-phosphorylated (p)-PKA (cat. no. 4781), anti-AMPK (cat. no. 5831) and anti-p-AMPK (cat. no. 2535) (all Cell Signaling Technology, Inc.). The secondary antibody used was Goat anti-Rabbit IgG (H+L)-HRP (cat. no. S0101-100; Beijing Lamblide Trading Co., Ltd.) at a dilution of 1:5,000.

Signaling pathway inhibition. Cells were pretreated with or without 10 µM H89 (a potent inhibitor of PKA; cat. no. T6250) (31) or 10 µM Dorsomorphin (an effective inhibitor of AMPK; cat. no. T1977; both TargetMol) (32) for 1 h, then cultured for 48 h with or without unOC.

Statistical analysis. Data are expressed as the mean ± standard deviation. Statistical analyses for two groups were performed using the two-tailed paired Student's t-test. Examination of more than two groups was conducted using one-way ANOVA using SPSS software (version 19.0; IBM Corp.). Bonferroni's correction method was performed as a post hoc test after one-way ANOVA. P<0.05 was considered to indicate a statistically significant difference.

**Results**

**ODI induces osteogenic differentiation of BMSCs**. First, the osteogenic differentiation potential of BMSCs was determined. In contrast to undifferentiated BMSCs, differentiated osteoblasts accumulate a large amount of extracellular calcium deposits (mineralization). This process is accompanied by the formation of bone nodules (33). Osteoblast-mediated mineralization is therefore indicative of the formation of bone mass and can be specifically detected using Alizarin Red S (34,35). Confluent fourth passage cells were cultured in the same medium containing ODI and control cells were cultured in the same medium without ODI. After 3 weeks, cells were stained with Alizarin Red to gauge the degree of osteogenic differentiation. The ODI-treated group was observed to have more calcium nodules compared with the control group (Fig. 1C and D). In addition, the NG + ADI group showed more lipid droplets than the NG group (Fig. 1A and B). The quantitative results were statistically significant, indicating that BMSCs had the potential for osteogenic differentiation and adipogenic differentiation (Fig. 1E and F).

**unOC promotes osteogenic differentiation of BMSCs and inhibits adipogenic differentiation through SIRT1 deactivation of RUNX2 and PPARγ**

**unOC promotes osteogenic differentiation of BMSCs**. To determine the effect of unOC on osteogenic differentiation, the BMSCs were divided into four groups: NG, unOC, NG + ODI And unOC + ODI. Alizarin Red staining was performed after 3 weeks of culture. It was found that the unOC group had more calcium nodules compared with the NG group (Fig. 2A and B). Similar results were observed in the NG + ODI group, indicating that unOC can function in the same manner as ODI to promote the differentiation of BMSCs into osteoblasts (Fig. 2C). In addition, the number of calcium nodules in the unOC + ODI treatment group was higher compared with that in the NG + ODI group (Fig. 2D). Quantification of Alizarin Red-positive areas indicated that significant increase in unOC and unOC + ODI groups compared with that in the NG group (Fig. 2E), suggesting that unOC can promote and facilitate the differentiation of mouse BMSCs into osteoblasts.

**unOC promotes osteogenic differentiation of BMSCs and inhibits adipogenic differentiation through SIRT1**. To assess whether unOC-induced osteogenic differentiation of BMSCs was mediated by SIRT1, transient transfection analysis was performed using SIRT1 siRNA and RT-qPCR analysis was used to determine that expression levels of two differentiation-related factors, ALP and OSX. Cells were divided into four groups: NG + NC, unOC Treatment + NC group, SIRT1 siRNA group and SIRT1 siRNA and unOC treatment group (unOC + SIRT1). RT-qPCR analysis showed that the expression levels of Sirt1, Alp and Osx significantly increased in the unOC + NC treatment group compared with the NG + NC group (Fig. 3A-C). In contrast, the expression levels of Alp and Osx significantly decreased in the SIRT1 siRNA transient transfected group compared with the NG + NC group. Moreover, their expression could not be recovered even when unOC was applied, suggesting that unOC promotes the
osteogenic differentiation of mouse BMSCs through SIRT1 and that unOC cannot counteract the effects of SIRT1 siRNA.

To determine whether unOC inhibits adipogenic differentiation through SIRT1, two notable factors associated with adipogenic differentiation were examined, FAS and FABP4. It was observed that \textit{Fas} and \textit{Fabp4} expression levels decreased in the unOC treatment group, indicating that unOC inhibited the adipogenesis of mouse BMSCs (Fig. 3D and E). The expression levels of \textit{Fas} and \textit{Fabp4} significantly increased in the SIRT1 siRNA-transfected group compared with those in the NG + NC group. After knocking down SIRT1, this increase was not reversible even after reintroducing unOC, indicating that the inhibition of the adipogenic differentiation by unOC was mediated by SIRT1.

\textit{unOC regulates BMSC differentiation through SIRT1 deacetylation of RUNX2 and PPARγ}. To determine whether the ability of unOC to regulate osteogenic differentiation was mediated through the acetylation function of SIRT1, SIRT1’s downstream targets, RUNX2 and PPARγ, were examined. Cells were divided into four groups: NG + NC, unOC + NC, SIRT1 siRNA and SIRT1 siRNA + unOC. Western blot analysis was performed in the total cell lysates for each group. It was found that unOC treatment significantly reduced the acetylation levels of PPARγ and RUNX2 compared with those in the NG + NC group. By contrast, their acetylation levels increased after SIRT1-knockdown (Fig. 4A, B, D and E). The acetylation states of PPARγ and RUNX2 have opposite effects on their activity and the PPARγ activity is enhanced in the acetylation state (22,36). Therefore, SIRT1 can reduce the activity of PPARγ and inhibit adipogenic differentiation. The results of the present study suggested that unOC deacetylated PPARγ through SIRT1 and downregulated the activity of PPARγ, thereby inhibiting the differentiation of BMSCs into adipocytes.

To further confirm that unOC inhibited the adipogenic differentiation of BMSCs by upregulating SIRT1, the adipogenic differentiation-related factor, C/EBPα, was analyzed and its expression was examined in four groups of cells: NG + NC, unOC + NC, SIRT1 siRNA and SIRT1 siRNA + unOC. It was found that SIRT1-knockdown resulted in marked increases in the C/EBPα protein abundance (Fig. 4C).
and mRNA expression levels (Fig. 4G) as compared with those in the control (NG + NC) group. unOC + NC treatment significantly decreased the expression level of C/EBPα compared with the NG + NC group and the SIRT1 siRNA group (Fig. 4C and G). There was no significant difference in C/EBPα expression between the unOC + SIRT1 siRNA treatment group and the SIRT1 siRNA group. The protein expression levels of SIRT1 markedly increased in the unOC + NC treatment group compared with those in the NG + NC group (Fig. 4C and F). By contrast, the expression levels of SIRT1 were markedly decreased in the SIRT1 siRNA group compared with those in the NG + NC group. There was no significant difference between the unOC + SIRT1 siRNA treatment group and the NG + SIRT1 siRNA group. Collectively, the data suggested that the regulation of SIRT1 by unOC in BMSCs inhibited adipogenic differentiation and, thus, promoted osteogenic differentiation.

**unOC promotes osteogenic differentiation of BMSCs through PKA-AMPK-SIRT1**

unOC can upregulate the expression levels of p-PKA, p-AMPK and SIRT1. As PKA and AMPK regulate SIRT1 in cell differentiation (37,38), the PKA-AMPK pathway was examined to find if it was required for unOC to promote osteogenic differentiation in BMSCs. The PKA inhibitor, H89, was used to detect the signaling pathway through which unOC regulated the differentiation of mouse BMSCs. It was found that unOC treatment significantly increased the protein level of p-PKA, p-AMPK and SIRT1 in BMSCs compared with their expression in the NG group (Fig. 5A-D). In contrast, the increased expression levels were completely abolished and even reversed by H89, while the expression levels of PKA and AMPK remained the same, indicating that unOC positively regulated the PKA-AMPK-SIRT1 pathway by upregulating p-PKA and p-AMPK. Furthermore, simultaneous treatment
with H89 and unOC restored the expression of p-PKA, p-AMPK and SIRT1 (Fig. 5). Collectively, the data indicated that unOC functioned upstream of the PKA-AMPK-SIRT1 pathway, thereby promoting the expression levels of p-AMPK and SIRT1.

**unOC regulates the differentiation of BMSCs through the PKA-AMPK-SIRT1 pathway.** To study the unOC-regulated PKA signaling pathways involved in the differentiation of mouse BMSCs, the AMPK inhibitor, Dorsomorphin, was examined using western blot analysis. Compared with the NG group, the levels of p-AMPK, p-PKA and SIRT1 were significantly increased in the unOC group, but there was no obvious trend in total PKA (Fig. 6). This change also appeared in the comparison between the NG + Dorsomorphin group and the unOC + Dorsomorphin group (Fig. 6). However, in the NG + Dorsomorphin group compared with the NG group, or the unOC + Dorsomorphin group compared with the unOC group, there was no statistical difference between P-PKA and total PKA. This is related to Dorsomorphin only inhibiting AMPK, but also indicates that AMPK is a downstream regulator of PKA (Fig. 6). After treating cells with Dorsomorphin, the phosphorylation of AMPK and SIRT1 in the NG + Dorsomorphin decreased compared with that in the NG group, but that of PKA did not change significantly (Fig. 6B-D). In addition, after adding Dorsomorphin and unOC to the BMSCs, both p-AMPK and SIRT1 expression levels were restored to similar levels of the NG group. These results indicated that unOC upregulated the expression of PKA, increased the phosphorylation level of the downstream target AMPK and promoted the expression of SIRT1. Through the aforementioned experiments, it was concluded that unOC promoted the osteogenic differentiation of mouse BMSCs through the PKA-AMPK-SIRT1 pathway.

**Discussion**

Previous studies have shown that the differentiation of BMSCs plays a noteworthy role in osteoporosis treatment as a therapeutic application (39-41). BMSCs can differentiate into osteoblasts, which can serve important functions in the synthesizing bone matrix (42). Osteoblasts, as the key cells for mediating bone formation, are embedded into the bone tissue...
after the mineralization process to eventually become bone cells and form one of the most important components of the bone (43). Studies have shown that osteoporosis is related to the adipogenic differentiation and aging of BMSCs (40,44). At the same time, promoting the osteogenic differentiation of BMSCs has predictable help in treating or reducing osteoporosis (45,46). Although the regulation and shift of the cell differentiation of BMSCs to osteoblasts rather than adipocytes is needed for the treatment of osteoporosis, the molecular mechanism responsible for this regulation of BMSCs has not been defined (39). Our previous study showed that unOC can regulate the differentiation shift of BMSCs to osteoblasts (16), suggesting its role as a potential treatment candidate for osteoporosis. The current study provided insights into the underlying mechanisms by identifying the downstream unOC regulatory pathway and the critical factor, SIRT1.

SIRT1, a core member of the sirtuin family of proteins, is an NAD+−dependent deacetylase. The main function of SIRT1 is to deacetylate histones and non-histone proteins in an organism (47). It affects cell proliferation, differentiation, metabolism, autophagy (48), cancer (49), inflammation, diabetes (50), osteoporosis (51) and other diseases closely associated with the health and aging of the body (52). It also plays an important role in regulating the differentiation of BMSCs. BMSC-specific SIRT1-knockout mice display reduced cell proliferation and accelerated cell senescence (53).

In contrast, the overexpression of SIRT1 delays senescence in BMSCs, which extends the cell life span in vitro, and the cells do not lose the potential for osteogenic and adipogenic differentiation (53). These findings uncovered potential therapeutic applications of BMSCs in tissue engineering (54). SIRT1 also prevents senescence in human BMSCs (53), suggesting a regulatory role for SIRT1 in the proliferation and differentiation of MSCs in humans. The present study found that the expression of SIRT1 is positively regulated by unOC in BMSCs, suggesting that SIRT1 is likely to play a role in mediating the effect of unOC on BMSC differentiation.

The dynamic balance between bone formation and bone resorption is the basis of bone remodeling and homeostasis (55). In addition to regulating the differentiation of MSCs (56), SIRT1 is also involved in the regulation of bone metabolism in the body (57,58). It maintains the normal bone remodeling process by regulating factors that are associated with bone metabolism, such as SOX9, PPARγ, NF-κB and RUNX2. SIRT1 deacetylates SOX9 and PPARγ, enhances SOX9 activity and reduces PPARγ activity, thereby regulating the differentiation of MSCs into chondrocytes and inhibiting their differentiation into adipocytes (22). SIRT1 inhibits NF-κB signaling to maintain normal skeletal remodeling (59).

SIRT1 is known to play a notable role in bone metabolism by promoting osteoblast differentiation, inhibiting osteoclast formation and reducing osteolysis (57,59). First, SIRT1

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**Figure 4.** unOC regulates the differentiation of BMSCs through SIRT1 deacetylation of RUNX2 and PPARγ. Western blot analysis of the total and acetylated (A) RUNX2 and (B) PPARγ. (C) Western blot analysis of SIRT1 and C/EBPα protein expression levels in the cell lysates of the four treatment groups after transfection with the lentiviral vector or vector control. Ratios of acetylated protein:total protein of (D) RUNX2 and (E) PPARγ. Gray value analysis of (F) SIRT1 and (G) C/EBPα. Experiments were repeated at least three times. *P<0.05, **P<0.01 vs. unOC + NC; #P<0.05, ##P<0.01 vs. NG + SIRT1 siRNA. unOC, uncarboxylated osteocalcin; BMSCs, bone marrow-derived mesenchymal stem cells; SIRT1, sirtuin 1; RUNX2, runt-related transcription factor 2; PPARγ, peroxisome proliferator-activated receptor γ; C/EBPα, CCAAT-enhancer-binding protein α; NG, normal group; NC, negative control; si-small interfering. C/EBPα, CCAAT-enhancer-binding protein α.
promotes osteogenic differentiation and inhibits adipogenic differentiation in human dental pulp stem cells by regulating the Wnt/β-catenin signaling pathway (20,60). Second, SIRT1 is a positive regulator of the osteoblast transcription factor, RUNX2. RUNX2 is one of the key osteogenic cytokines (61,62). RUNX2-deficient mice exhibit a complete absence of mature osteoblasts and obvious defects in bone mineralization (63). Zainabadi et al (21) found that SIRT1-deficient mice had lower expression levels of RUNX2 downstream targets, including osteopontin and OSX, and decreased osteogenic differentiation. In contrast, MSCs treated with SIRT1 agonists show decreased RUNX2 acetylation, increased expression levels of RUNX2 targets and enhanced osteoblast differentiation. Thirdly, SIRT1 inhibits the osteoclast process by regulating the NF-κB signaling pathway. NF-κB is a type of nuclear transcription factor associated with cellular immunity, apoptosis and differentiation. The activation of NF-κB promotes the receptor activator of nuclear factor-κB ligand-induced osteoclast formation (64). SIRT1 and NF-κB have a mutual inhibitory relationship. The SIRT1 activator, resveratrol, activates the expression of NF-κB inhibitory protein α. Furthermore, SIRT1 directly inhibits NF-κB signaling by deacetylating the p65 subunit of the NF-κB complex and inhibits its accumulation in the nucleus (65). Thus, the inhibition of NF-κB signaling reduces the formation of osteoclasts and adipocytes and increases the number of osteoblasts, which further reduces bone resorption, increases bone formation, restores bone mass and corrects bone metabolism imbalance (51). In contrast, NF-κB downregulates SIRT1 activity through decreased intracellular NAD⁺ levels (66). Thus, both NF-κB and SIRT1 restrict each other and participate in the regulation of osteogenic differentiation and bone metabolism.

In summary, SIRT1 has potential for restoring bone metabolism and treating osteoporosis by regulating the osteogenic differentiation of MSCs. The findings of the present study are consistent with previous reports that SIRT1 deacetylates RUNX2 and PPARγ and regulates their activity (67). unOC treatment was also found to upregulate SIRT1 expression, which lead to increased deacetylation of RUNX2 and PPARγ. According to a previous study, the activity of RUNX2 was enhanced after deacetylation whereas the activity of deacetylated PPARγ was reduced, thereby promoting the differentiation of BMSCs into osteoblasts and inhibiting their differentiation into adipocytes (21,22).

unOC promotes BMSC differentiation and inhibits adipogenesis through SIRT1, which may serve as a novel target for osteoporosis treatment (68). Studies have shown that unOC has a wide range of biological functions. It is involved in vital life processes, such as differentiation, metabolism and cognition (69-73). unOC also plays an active role in the regulation of bone metabolism (74), cardiovascular disease (75) and melanoma (76).
Multiple lines of evidence indicate that unOC is involved in BMSC differentiation. Studies have shown that mineral maturation and total hydroxyapatite content are reduced as a result of decreased levels of the osteocalcin gene in BMSCs (77-79). This suggests that osteocalcin can be induced by promoting bone differentiation (80) and is conducive to the recovery of bone metabolism (81). Our previous studies have shown that unOC stimulates the differentiation of pre-bone MC3T3-E1 cells (27) and BMSCs (16) into bone cells. The present study demonstrated that unOC promoted osteogenic differentiation and inhibited adipogenic differentiation in BMSCs via the PKA-AMPK-SIRT1 signaling pathway as the PKA inhibitor, H89, abolished the upregulation of SIRT1, p-PKA and AMPK via unOC. Moreover, treatment with Dorsomorphin, an AMPK inhibitor, reversed the effect of unOC on SIRT1 and AMPK, but not on PKA. These findings suggested that unOC functioned via the PKA-AMPK-SIRT1 pathway in regulating BMSC differentiation. However, Dorsomorphin is also an inhibitor to bone morphogenetic protein (BMP), which is known to be involved in adipogenesis (82,83). Therefore, it is possible that BMP also plays a role in mediating the function of unOC on BMSC differentiation. Further studies are required to confirm this theory.

There are some limitations in the present study. First of all, the cells used in the present study were extracted from the femur of C57 mice, which are different from the BMSCs of humans (84,85). Especially the osteoarthritis of patients with osteoarthritis will show higher levels of osteocalcin and type I collagen (86). In addition, used 3rd to 5th generations of BMSCs were used from 4-week-old mice, where it has been reported that the pathological characteristics of patients with osteoporosis are significantly different in the early, middle and late stages (87). Therefore, future research would need to involve the comparison of the treatment effects of unOC on osteoporosis at different pathological stages.

The present study provided several lines of evidence that SIRT1 was a key target of unOC-mediated regulation of BMSC differentiation into osteoblasts. Firstly, unOC directly shifted the differentiation potential via SIRT1. SIRT1 was required for unOC-mediated upregulation of pro-osteogenic differentiation factors, ALP and OSX, and unOC-induced downregulation of pro-adipogenic differentiation factors, FAS and Fabp4. Secondly, unOC shifted the differentiation potential of BMSCs via SIRT1 by inducing the deacetylation of the downstream targets, RUNX2 and PPARγ. Finally, unOC upregulated SIRT1 expression through the PKA-AMPK pathway. Collectively, these data indicated that unOC has the potential to promote the differentiation of BMSCs into osteoblasts or tissue regeneration, suggesting its potential in clinical practice, especially in the treatment of osteoporosis.
Acknowledgements

Not applicable.

Funding

The present study was supported by grants from The Knowledge Innovation Program of The Chinese Academy of Sciences (grant nos. KSCX2-EW-J-29 and Y129015EA2) and The College of Life Sciences, University of Chinese Academy of Sciences (grant no. KJRH2015-006).

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Authors’ contributions

LG designed and performed the majority of the investigation and performed data analysis. FZG and JHY contributed to the interpretation of the data and analyses. All authors have read and approved the final manuscript. LG and FZG confirm the authenticity of all the raw data.

Ethics approval and consent to participate

The present study was approved by The Institutional Animal Care and Use Committee of The University of Chinese Academy of Sciences (Beijing, China).

Patient consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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