

Bone-Targeting Liposome-Encapsulated Salvianic Acid A Improves Nonunion Healing Through the Regulation of HDAC3-Mediated Endochondral Ossification

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Limin Zhou,^{1,*}
Haojun Wu,^{2,*}
Xiang Gao,^{2,*}
Xiaoyan Zheng,¹
Hang Chen,² Hailong Li,¹
Jun Peng,¹ Weichong Liang,¹
Wenxing Wang,¹
Zuocheng Qiu,³
Anjaneyulu Udduttula,³
Kefeng Wu,¹ Lin Li,⁴
Yuyu Liu,¹ Yanzhi Liu^{1,3}

¹Guangdong Key Laboratory for Research and Development of Natural Drugs, Department of Pharmacology, Guangdong Medical University, Zhanjiang, Guangdong 524023, People's Republic of China;

²Department of Orthopaedics, Stem Cell Research and Cellular Therapy Center, The Affiliated Hospital of Guangdong Medical University, Zhanjiang, Guangdong 524001, People's Republic of China; ³Translational Medicine R&D Center, Institute of Biomedical and Health Engineering, Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen 518055, People's Republic of China; ⁴School of Pharmaceutical Sciences, Southern Medical University, Guangzhou 510515, Guangdong Province, People's Republic of China

*These authors contributed equally to this work

Correspondence : Yanzhi Liu
Email liuyanzhi02@163.com

Yuyu Liu
Email liuyuyu77@163.com

Aim: Nonunion is a major complication in fracture repair and remains a challenge in orthopaedics and trauma surgery. In this study, we aimed to evaluate the effectiveness of treatment of nonunion with a large radial defect using a bone-targeting liposome-encapsulated salvianic acid A (SAA-BTL)-incorporated collagen sponge and further elucidate whether the effects were closely related to histone deacetylase 3 (HDAC 3)-mediated endochondral ossification in nonunion healing process.

Methods: Fifteen New Zealand female rabbits were randomly divided into three groups. Segmental radius critical size defects (15 mm) were created via surgery on both the forelimbs of the rabbits. The SAA-BTL/SAA/saline-incorporated collagen sponges were implanted into the defects in the three groups, respectively, for four weeks of treatment. X-ray imaging, micro-computed tomography (CT) analysis, histology, and immunofluorescence analysis (HDAC3, collagen II, VEGFA, and osteocalcin) were performed to determine the effects of the treatments. In addition, a short interfering RNA was applied to induce HDAC3 knockdown in the chondrogenic cell line ATDC5 to investigate the roles of HDAC3 and SAA intervention in endochondral ossification in nonunion healing.

Results: X-ray imaging and micro-CT results revealed that SAA-BTL-incorporated collagen sponges significantly stimulated bone formation in the nonunion defect rabbit model. Furthermore, immunofluorescence double staining and histology analysis confirmed that SAA-BTL significantly increased the expression of P-HDAC3, collagen II, RUNX2, VEGFA, and osteocalcin in vivo; accelerated endochondral ossification turnover from cartilage to bone; and promoted long bone healing of nonunion defects. ATDC5 cells knocked down for HDAC3 showed significantly decreased expression of HDAC3, which resulted in reduced expression of chondrogenesis, osteogenesis, and angiogenesis biomarker genes (Sox9, Col10a1, VEGFA, RUNX2, and Col1a1), and increased expression of extracellular matrix degradation marker (MMP13). SAA treatment reversed these effects in the HDAC3 knockdown cell model.

Conclusion: SAA-BTL can improve nonunion healing through the regulation of HDAC3-mediated endochondral ossification.

Keywords: nonunion, fracture, HDAC3, endochondral ossification, bone-targeting liposome, salvianic acid A

Introduction

Nonunion defects are among the most challenging clinical complications in the repair of bone fractures.^{1,2} Nonunion mainly occurs as a result of fixation

instability, aging, therapeutic interference (eg, treatment with glucocorticoids), infection, higher Gustilo grade fractures, and some diseases (eg, diabetes). Approximately 5% to 10% of all fractures develop into delayed or nonunion fractures. Research suggests that approximately 17% of all open long bone fracture cases develop into nonunion and 8% of these cases develop delayed union.^{3–6} The mechanism underlying these progressions is multifactorial and their treatment can be difficult, complex, and expensive. At present, the options for treatment of nonunion include surgical autograft/allografts,^{7,8} BMP-loaded bone substitutes,^{9,10} and physical therapy (low-intensity pulsed ultrasound).^{11,12} All these interventions have limitations, including limited autograft materials, high cost, treatment efficacy issues, and adverse side effects. In addition, there is a lack of approved pharmacological agents that can be used for the treatment of established nonunion or for acceleration of fracture healing. The unmet clinical needs and unknown nature of the underlying mechanisms of nonunion make this an ideal topic for further studies.

In previous study,¹³ we reported a novel and yet simple bone targeting liposome (BTL) using pyrophosphorylated cholesterol (cholesterol-PPi) as the targeting ligand and developed a salvianic acid A (CAS#: 7682–21-4) loaded bone targeting liposome formulation (SAA-BTL) for treatment of fracture healing disorder. When locally administered in a glucocorticoid induced delayed fracture model, due to pyrophosphate has strong binding affinity to hydroxyapatite (HA), the SAA-BTL could bind to the bone via cholesterol-PPi's strong chelation to the bone apatite at different bone surfaces (including growth plate, trabecular bone, and cortical bone), providing significant local distribution of high concentration of SAA and improved retention (last beyond 20 days for one injection) of SAA at the fracture site to better augment the healing process. Therefore, SAA-BTL reveals its potential as a promising choice for nonunion treatment. The effectiveness of SAA-BTL treatment on healing of nonunions and the mechanism underlying nonunion are attractive topics that require further investigation.

Several studies have shown that SAA stimulates osteogenesis and angiogenesis by regulating WNT signalling and oxidative stress.^{14–18} However, the specific mechanism of SAA employed to accelerate fracture healing has not yet been fully elucidated. Relatively few studies have focused on the role of chondrogenesis, which involves the formation of cartilage that facilitates an initial union of most long bone fractures,^{6,19} or endochondral ossification, which plays a vital role in the process of bone tissue repair during long bone

fracture.^{20,21} Impaired endochondral ossification during fracture healing can result in delayed union or nonunion. Recent studies have found that histone deacetylase 3 (HDAC3) is involved in the regulation of extracellular matrix formation, cartilage development, endochondral ossification, and bone development.^{22–24} If HDAC3 is inhibited, fracture healing may be hindered due to impaired endochondral ossification. HDAC is a family of proteases that act as inhibitors of transcription by removing acetyllysine side chains from the tail of histone proteins. There are 18 types of proteases, which can be divided into four categories.^{25,26} Among the 18 HDAC proteins, HDAC3 is responsible for regulating multiple cell types involved in bone healing.²⁷ Our previous study indicated that SAA-BTL accelerates delayed fracture healing partly by stimulating endochondral ossification.

Therefore, we hypothesised that SAA and its bone targeting formulation may regulate HDAC3-mediated endochondral ossification during fracture healing, resulting in superior bone formation. In this study, we applied an SAA-BTL-incorporated collagen sponge in a rabbit model of radius critical size defects to evaluate its efficacy in treating long bone nonunion. The model used in this study is known for its significant proportion of nonunion (minimal bone regeneration; no significant bridging of callus tissue or solid unions), making it suitable for drug and/or biomaterial evaluation.^{28–30} No devices (including external/internal fixation, casts, or braces) are needed to stabilise the nonunion defect in critical-sized defect rabbit models because the ulna and radius are fused at the ends and the biomechanical load of the anterior part of the rabbit can be supported by the ulna.^{28,31} This ensures a higher degree of reproducibility between animal models.

In addition, we attempted to demonstrate that SAA-BTL-incorporated collagen sponge might accelerate nonunion healing through the regulation of HDAC3-mediated endochondral ossification. A series of *in vivo* and *in vitro* studies were also designed to identify the functional mechanisms underlying these effects. The findings of our study may advance our understanding of the underlying mechanism of nonunion and may provide valuable insights for the discovery of effective strategies and targets for nonunion therapy.

Materials and Methods

Formulation of Bone-Targeting SAA-Loaded Liposome

The liposome was formulated as previously described.¹³ Briefly, 150 mg lecithin, 27 mg cholesterol, and 11 mg

cholesterol-pyrophosphate were dissolved in 6 mL of dichloromethane. Then, 15 mg/mL SAA PBS solution (pH 7.4) was mixed with the dichloromethane solution, and the aqueous and organic phases were maintained at a 1:3 volume ratio. The mixed solution was stirred at 1500 rpm under the protection of nitrogen for 10 min. Dichloromethane was removed from the resulting emulsion by rotating evaporation for 2 h at 26 °C. The resulting liposomes were extruded through an Avanti® Mini-Extruder equipped with a 0.2 µm membrane (Avanti Polar Lipids, AL, USA) to obtain the desired size. The liposomes were then purified using a pre-packed desalting column (PD-10) containing Sephadex G-25 (GE Healthcare Life Sciences, USA) to remove any free SAA according to manufacturer's protocol.

Characterization of SAA-BTL Liposomes

A dynamic light scattering (DLS) system (Zetasizer Nano ZS90, Malvern Instruments, Worcestershire, UK) was used to determine the effective hydrodynamic diameters, polydispersity index (PDI) and ζ-potential of SAA-BTL. SAA calibration was first established on the ÄKTA Fast protein liquid chromatography (FPLC) system using a Superdex 200 column, a PBS (0.05 M) mobile phase and the detection wavelength of 282 nm. To quantify the loading efficiency of SAA in the liposomes, both SAA-BTL and SAA-NTL were formulated as described above and immediately separated from the free SAA on the FPLC system. The SAA was quantified according to a SAA calibration. The loading efficiency of the liposome formulation was then calculated according to the following equation:

$$\text{Loading efficiency} = \left(1 - \frac{\text{free SAA}}{\text{total SAA}}\right) \times 100$$

Table I The Characterization of SAA-BTL Liposomes

Parameters	SAA-BTL
Z-Average (d. nm)	167.6
PDI	0.138
ζ-Potential (mV)	-50.15
Lec/Chol/Chol-P/SAA*	38/14/3/30
SAA Loading Efficiency (%)	33.1

Note: *Molar ratio.

Abbreviations: Lec, lecithin; Chol, cholesterol; Chol-P, cholesterol-PPi; SAA, salivianic acid A.

Live/Dead Assay and Cell Morphology Observation

The chondrogenic ATDC5 cell line was purchased from the European Cell Culture Collection (ECACC; Salisbury, Wiltshire, UK). Sterile collagen sponges were cut into 1 mm thick slices. ATDC5 cells (5×10^4 cells) were seeded onto each type of collagen sponge and cultured in 24-well plates for 24 h. Then, the cell-laden sponges were stained using a Live/dead Staining Kit (KTA1001, Abbkine) according to the manufacturer's protocol. Sponges were imaged using a confocal ultrahigh-resolution microscope (SpinSR10, OLYMPUS, Japan) with a 488 nm filter for living (green) and 561 nm filter for dead (red) cells. At least six images were captured per sample at different random locations. Live and dead cells were measured automatically using Image Pro Plus 6.0 software (Media Cybernetics, Inc., MD, USA).

To visualise cell morphology, ATDC5 cells were seeded onto SAA/SAA-BTL-incorporated collagen sponges and cultured for 48 h, followed by staining with phalloidin (Phalloidin-iFluor 594, ab176757, Abcam, Cambridge, UK) diluted at 1:100 and counter-staining of cell nuclei with DAPI diluted at 1:500, which allowed the observation of actin cytoskeleton. The samples were imaged using a confocal ultrahigh-resolution microscope (SpinSR10, OLYMPUS, Japan).

Effects of SAA-BTL-Incorporated Collagen Sponge Treatment on a Nonunion Rabbit Model

The animal experiments were performed in strict accordance with the guiding principles for the Care and Use of Laboratory Animals of Guangdong Laboratory Animal Monitoring Institute (Approval number: GDY1702015) and the National Laboratory Animal Monitoring Institute of China. Collagen sponges (Beijing Yierkang Bioengineering Co., Ltd, Beijing, China) were cut into 2×0.5 cm pieces and were then incorporated with sterile saline (500 µL), SAA (5 mg/kg rabbit, 500 µL, Chengdu Must Bio-Technology Co., Ltd, Chengdu, China), and SAA-BTL (5 mg/kg rabbit, 500 µL) and implanted into the animals. Then, 15 New Zealand female rabbits were randomly divided into three groups (weight, 2.5–3 kg, obtained from Huadong Xinhua Experimental Animal Center, Guangzhou, China). The groupings were as follows: control (nonunion rabbits treated with saline-incorporated collagen sponges, n=5), SAA (nonunion

rabbits treated with SAA-incorporated collagen sponges, $n=5$), and SAA-BTL (nonunion rabbits treated with SAA-BTL-incorporated collagen sponges, $n=5$). Radius critical size defects were created on both the forelimbs of the rabbits to mimic long bone nonunion as described previously.^{28,31,32} Briefly, each rabbit was anaesthetised with isoflurane, and after both the forelimbs of the rabbits were shaved and disinfected with iodine, a low-speed handsaw was used to create a 15 mm segmental defect in the middle of the diaphysis of the radius. The treatment sponge was implanted into the defect and three-layer sutures were used to close the wound. Bandage of the surgery site was changed and the wound was disinfected daily for 7 days. Antibiotic medication (40,000 IU penicillin per animal per day) was intramuscularly injected after the operation for 3 days to prevent infection. Carprofen (4 mg/kg body weight) was given to all the rabbits daily for 3 days for pain relief. The rabbits were housed in single cages in the institutional animal laboratory according to animal care regulations (automatic light-dark cycle, with water and food ad libitum).

An X-ray imaging system (In-Vivo MS FX Pro Optical/X-ray system, Bruker, USA) was used to monitor fracture healing at one and four weeks post-surgery until euthanasia. Rabbits were euthanised after four weeks of treatment and samples were collected for micro-computed tomography CT (Viva CT 40, SCANCO Medical, Switzerland), immunofluorescence, and histology analyses.

Micro-CT Analysis of Nonunion Healing

Rabbit radius samples were scanned horizontally by micro-CT (Viva CT 40, SCANCO Medical, Switzerland). The X-ray energy/intensity was set to 70 kV, 114 μ A, 8 W, on a 1200 mg HA/ccm block for calibration. The scan integration time was 200 ms. The region spanning 2.5 mm on either side of the middle line of the defect was chosen as the region of interest (ROI). Bone volume (BV), tissue volume (TV), and BV/TV were measured according to the ROI.

Histology Analysis of Nonunion

Rabbit radius samples were decalcified for 30 days in 12% EDTA working solution. The samples were then embedded in paraffin for histological analysis. The paraffin-embedded samples were sectioned (5 μ m) and the sections were stained with safranin O and fast green.

Immunofluorescence Assay

Sample sections (5 μ m) were deparaffinised and rehydrated before commencing the immunofluorescence assay. The sections were placed in proteinase K working solution (50 μ g/mL) and incubated for 20 min at 37 °C in a humidified chamber. After antigen retrieval, samples were incubated with immunofluorescence blocking buffer (5% goat serum and 0.3% Triton X-100 mixed PBS working buffer) for 1 h at 37°C.

Then, double staining immunofluorescence assay was performed. P-HDAC 3 (3815S, 1:200, Cell Signaling) and RUNX2 (ab23981, 1:100, Abcam) were mixed with collagen II (ab3092, 1:100, Abcam) respectively in primary antibody diluent buffer. P-HDAC 3/collagen II, and RUNX2/collagen II require the same pre-treatment for immunofluorescence double staining. For both, the sections were covered with the mixed primary antibody diluent buffer and incubated overnight at 4 °C. On the other hand, osteocalcin (ab13421, 1:200, Abcam)/collagen II double staining, and VEGFA (ab1316, 1:200, Abcam)/collagen II double staining were performed primary antibody incubation one by one separately for each antibody. Specifically, osteocalcin or VEGFA primary antibody was added to each section and incubated overnight at 4 °C. Later, collagen II was added as the second primary antibody to the sections and the sections were incubated for 2 h. Following incubation, the sections were rinsed with PBS three times and incubated with FITC-conjugated secondary antibody (L3202; 1:200; SAB), CY3 conjugated secondary antibody (A22220; 1:200; Abbkine), Alexa Fluor 488-conjugated secondary antibody (A21121; 1:200; Invitrogen), or Alexa Fluor 555-conjugated secondary antibody (A21426; 1:200; Invitrogen) at 37 °C for 1 h. Next, the sections were rinsed with PBS, and antifade mounting medium containing DAPI was added to the sections for nuclear staining. Confocal ultrahigh-resolution microscope (SpinSR10, OLYMPUS, Japan) was used to capture fluorescence images. At least six images were randomly captured at different locations in the fracture defect (20 \times magnification) for each sample and collected for final analysis. The positive expression of collagen II, P-HDAC3, osteocalcin, RUNX2, and VEGFA in the region of fracture calluses was measured using Image-Pro Plus 6.0 software (Media Cybernetics, Silver Spring, MD, USA) and presented as integral optical density. The analysts were blinded to all image groupings.

Impact of SAA Treatment on Chondrogenic ATDC5 Cells

ATDC5 chondrogenic cells were used as a cell model to investigate endochondral ossification *in vitro*. ATDC5 chondrogenic cells show a sequential transition of phenotype *in vitro*, encompassing stages from mesenchymal condensation to calcification. ATDC5 chondrogenic cell line has been used for endochondral ossification research in a previous study.²²

ATDC5 cells were incubated in a 96-well plate at the concentration of 3×10^3 cells per well for the cell viability assay. Cells were treated with different concentrations of SAA. Six duplicate wells were established for each group and culture medium was replaced with fresh medium every two days. The MTT assay was used to quantify cell viability at 24, 48, and 72 h after SAA treatment. ATDC5 cells were incubated in a six-well plate at 5×10^5 cells per well. After 24 h, a short interfering RNA (siRNA) (Shanghai GenePharma Co., Ltd, Shanghai, China) was used to induce HDAC3 knockdown using Lipofectamine 3000 (Invitrogen). Cells were treated with SAA for 4–6 h of siRNA transfection and were cultivated for 48 h. HDAC3 protein expression was then determined by Western blotting. Expression of target genes including

HDAC3, Sox9, Col1a1, Col10a1, Aggrecan, and OPG was evaluated using RT-PCR after 72 h of SAA treatment.

Western Blotting Analysis

Protein samples were prepared in RIPA buffer on ice. Lysates were separated by centrifugation at $10,000 \times g$ and $4^\circ C$ for 10 min. SDS-PAGE was used to resolve 30 mg protein per sample. HDAC3 (85057S; 1:1000; Cell Signaling) and GAPDH (A01020; 1:1000; Abbkine) were used as primary antibodies. The samples were incubated with the primary antibodies overnight at $4^\circ C$, followed by incubation with goat anti-rabbit IgG (A21020; 1:5000; Abbkine) or goat anti-mouse IgG antibodies (A21010; 1:5000; Abbkine) for 1 h at $37^\circ C$. Bands were captured using a FluorChem[®] Q Imaging System (ProteinSimple, CA, USA) and measured using Image J software (NIH Image, Bethesda, MD, USA). Protein expression was normalised to that of GAPDH.

RT-PCR Analysis

Total RNA was harvested from ATDC5 cells using TRIzol reagent (TAKARA, Japan). Reverse transcription of total RNA to cDNA was performed using a commercial kit (RR036A, TAKARA, Japan). Selected genes (HDAC 3, Col1a1, VEGFA, Runx2, Aggrecan, OPG, Sox9, and

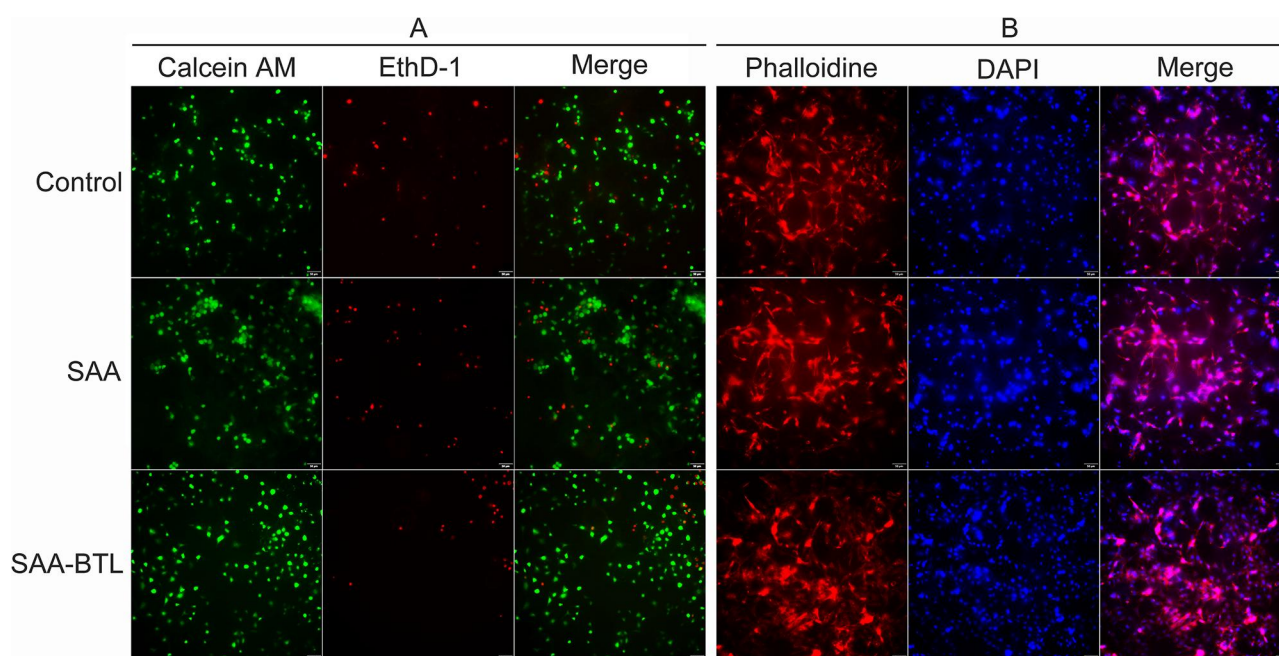


Figure 1 Live/dead assay and actin cytoskeleton observation of ATDC 5 cells seeded on SAA/SAA-BTL-incorporated collagen sponges. **(A)** Live/dead assay for ATDC 5 cells seeded on SAA/SAA-BTL-incorporated collagen sponges after 24h. **(B)** Cytoskeleton observation of ATDC 5 cells seeded on SAA/SAA-BTL-incorporated collagen sponges after 48h. Quantitative data from the Live/dead assay are shown in [Figure 7F](#).

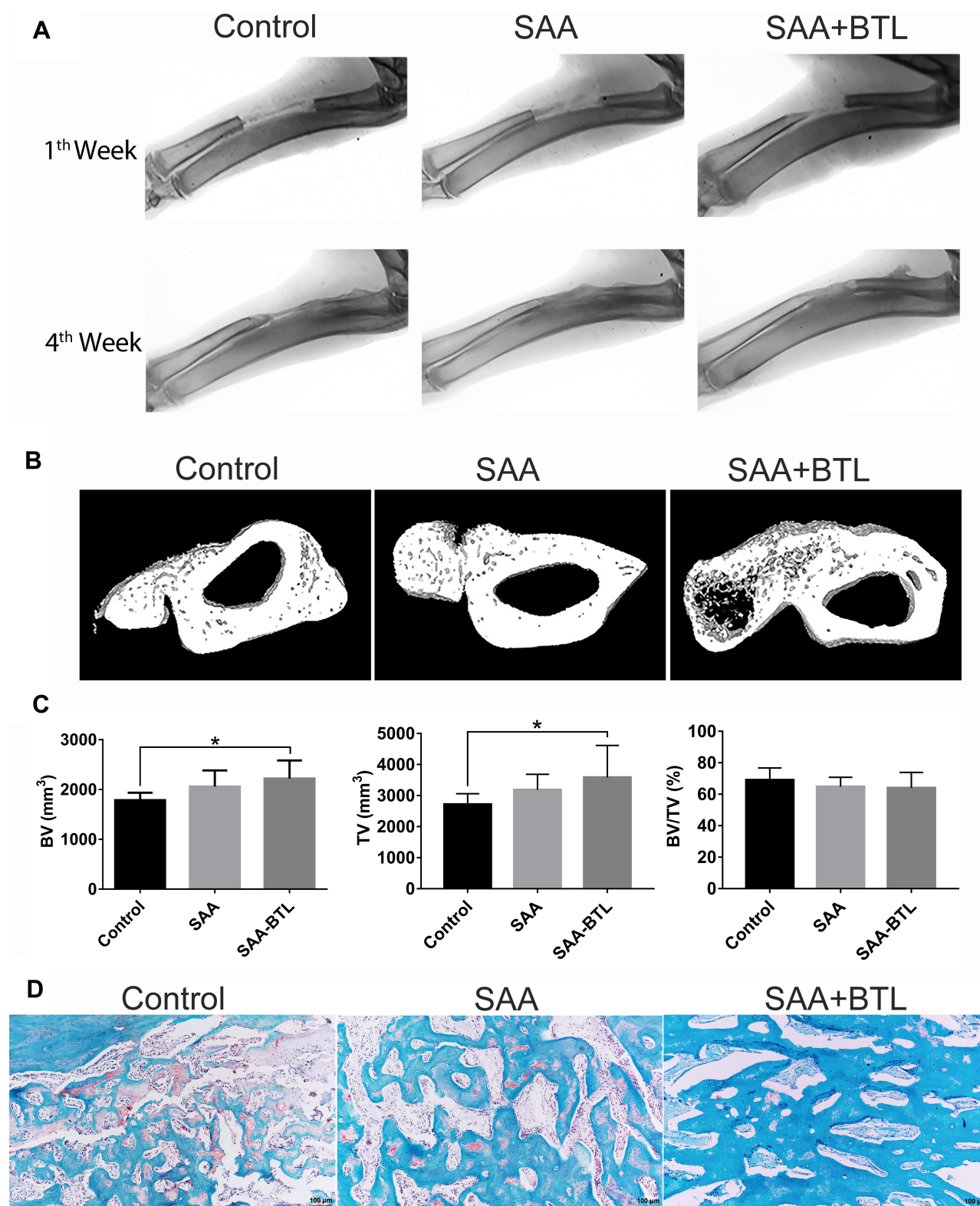


Figure 2 X-ray, micro-CT, and histology evaluations of fractured radius calluses from the rabbits of the control, SAA, and SAA-BTL group. **(A)** X-ray images from representative specimens at the 1st and 4th weeks post-fracture. **(B)** Micro-CT images of fracture calluses from representative samples at the 4th week post-surgery. **(C)** Micro-CT quantitative data of fracture calluses from different groups. The region of interest (ROI) was 2.5 mm below and above the middle line of the defect. BV, bone volume; TV, tissue volume; BV/TV, the ratio of bone volume to tissue volume. * $P < 0.05$. **(D)** Histologic images of fracture calluses from representative specimens at the 4th week post-surgery. Callus sample was stained with safranin O. The chondrocyte area shows red color within the callus.

Abbreviations: Control, nonunion rabbits treated with saline-incorporated collagen sponges; SAA, nonunion rabbits treated with salivianic acid A-incorporated collagen sponges; SAA-BTL, nonunion rabbits treated with bone-targeting liposome-encapsulated salivianic acid A-incorporated collagen sponges.

Col10a1) were subjected to real-time semi-quantitative PCR (qPCR) analysis (RR820A, TAKARA) with SYBR[®] Premix Ex Taq[™] II (RR820A, TAKARA, Japan). The analysis was performed on an ABI 7500-Fast Real-Time PCR System (Applied BioSystems, Foster City, USA). Reaction settings were as follows: first 95 °C for 30 s, followed by 40 cycles of 95 °C for 5 s and 60 °C for 34 s. The real-time PCR primers were synthesised as shown in [Supplementary Materials Table S1](#). The housekeeping gene GAPDH was used to normalise the target gene expression. The comparative threshold cycle ($2^{-\Delta\Delta C_t}$) calculation was used to quantify relative gene expression.

Statistical Analysis

Results are presented as mean±SD. The statistical differences among groups were analysed by one-way analysis of variance (ANOVA) with a Fisher's protected least significant difference (LSD) or Dunnett's T3 test. $P < 0.05$ was considered statistically significant. All analyses were

performed using SPSS 17.0 software (SPSS Inc., Chicago, IL, USA).

Results

Characterization of SAA-Loaded Liposomes

The DLS data revealed that SAA-BTL liposome has a hydrodynamic diameter of ~160 nm, a PDI of ~0.138, and a ζ -Potential of ~-50.15 mv. The SAA loading efficiency in BTL was determined to be ~33% by FPLC analysis. SAA was found to gradually release from SAA-BTL in α -MEM cell culture medium at 37 °C during 7 days ([Figure S1](#)).

Cell Survival and Cell Morphology of ATDC5 Cells Seeded on SAA/SAA-BTL-Incorporated Collagen Sponge

Live/dead cell staining images showed that the cell survival rate slightly increased in the SAA group after 24 h of

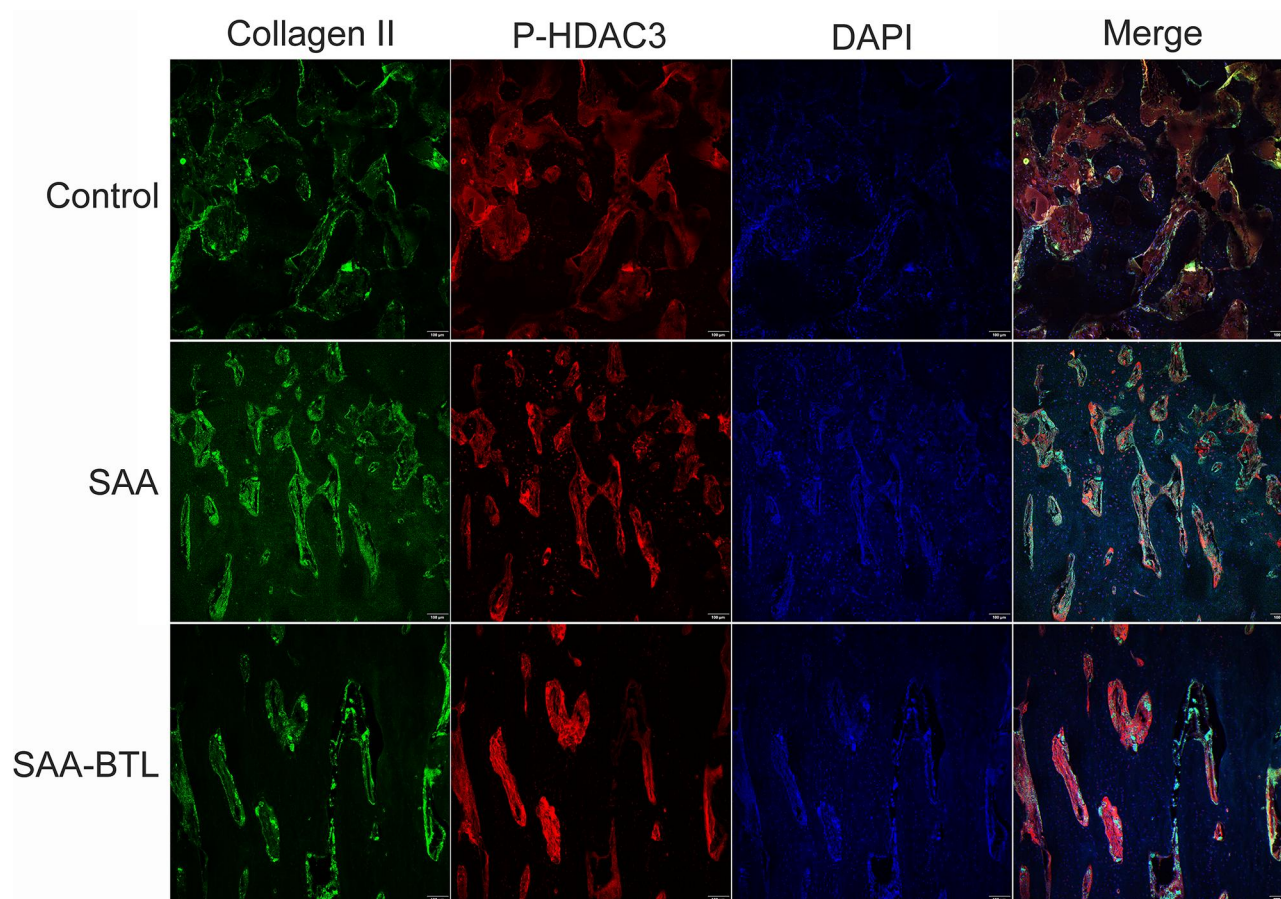


Figure 3 Immunofluorescence analysis of collagen II and P-HDAC 3 expression in fracture calluses at the 4th week post-surgery. P-HDAC3 and collagen II expression was quantified in sections of the callus. These data are shown in [Figure 7A](#).

cultivation compared to that in control, while the survival rate in the SAA-BTL group was significantly higher than that in the SAA and control groups (Figures 1A and 7F). The actin cytoskeleton of the ATDC5 cells in the control and SAA/SAA-BTL groups showed no significant alterations in shape or cytoskeleton structure after 48 h culture on SAA/SAA-BTL-incorporated collagen sponge. (Figure 1B).

SAA-BTL Treatment Promotes Nonunion Healing in Rabbits

In the 4th week post-surgery, we observed that the fracture defects in the control group rabbits demonstrated poor union callus formation, while rabbits with SAA and SAA-BTL treatment showed significantly increased union callus formation. The SAA and SAA-BTL treatments accelerated the healing of fractures (Figure 2A). Micro-CT and imaging data revealed that BV and TV were significantly elevated in the SAA-BTL compared to that in the control group (Figure 2B and C). Histology images showed that bone areas in the callus increased after SAA-BTL

treatment (Figure 2D), while there was decrease in the chondrocyte area compared to that in the control group. Immunofluorescence images showed that the expression of collagen II, P-HDAC3, and VEGFA in the callus was significantly increased in the SAA and SAA-BTL groups compared to that in the control. SAA-BTL-incorporated collagen sponge treatment significantly increased osteocalcin and RUNX2 expression compared to control and SAA treatments (Figures 3–6 and Figure 7A–E). These results demonstrate that SAA and its liposome formulation promote bone formation and P-HDAC3 expression at the fracture site of the radius nonunion rabbit model.

SAA and Its Formulation Stimulate the Terminal Stage of Endochondral Ossification Through the Regulation of HDAC3 Expression

SAA treatment did not significantly affect the viability of ATDC5 cells at different time points compared to the

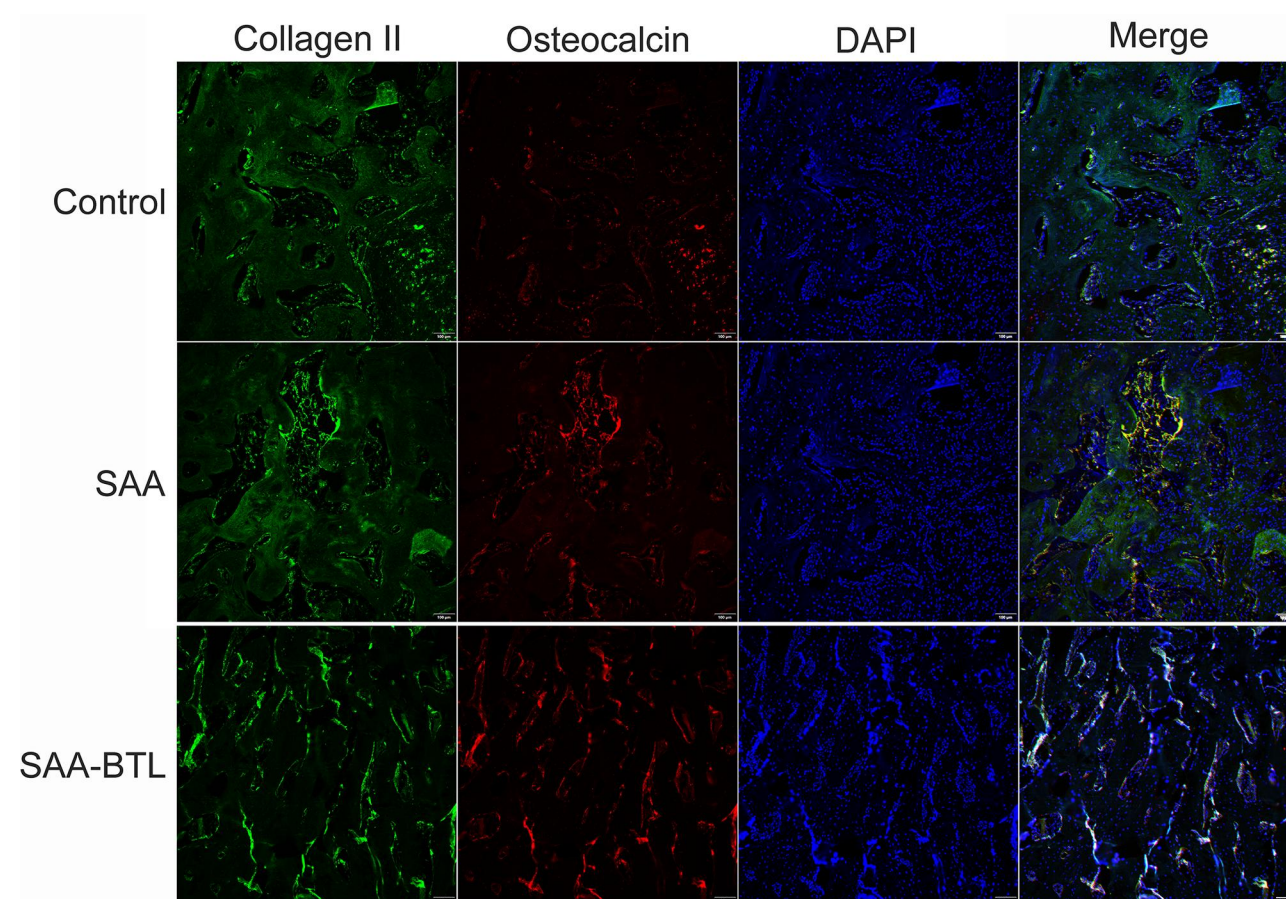


Figure 4 Immunofluorescence analysis of collagen II and osteocalcin expression in fracture calluses at the 4th week post-surgery. Osteocalcin and collagen II expression were quantified in sections of the callus. These data are shown in Figure 7B.

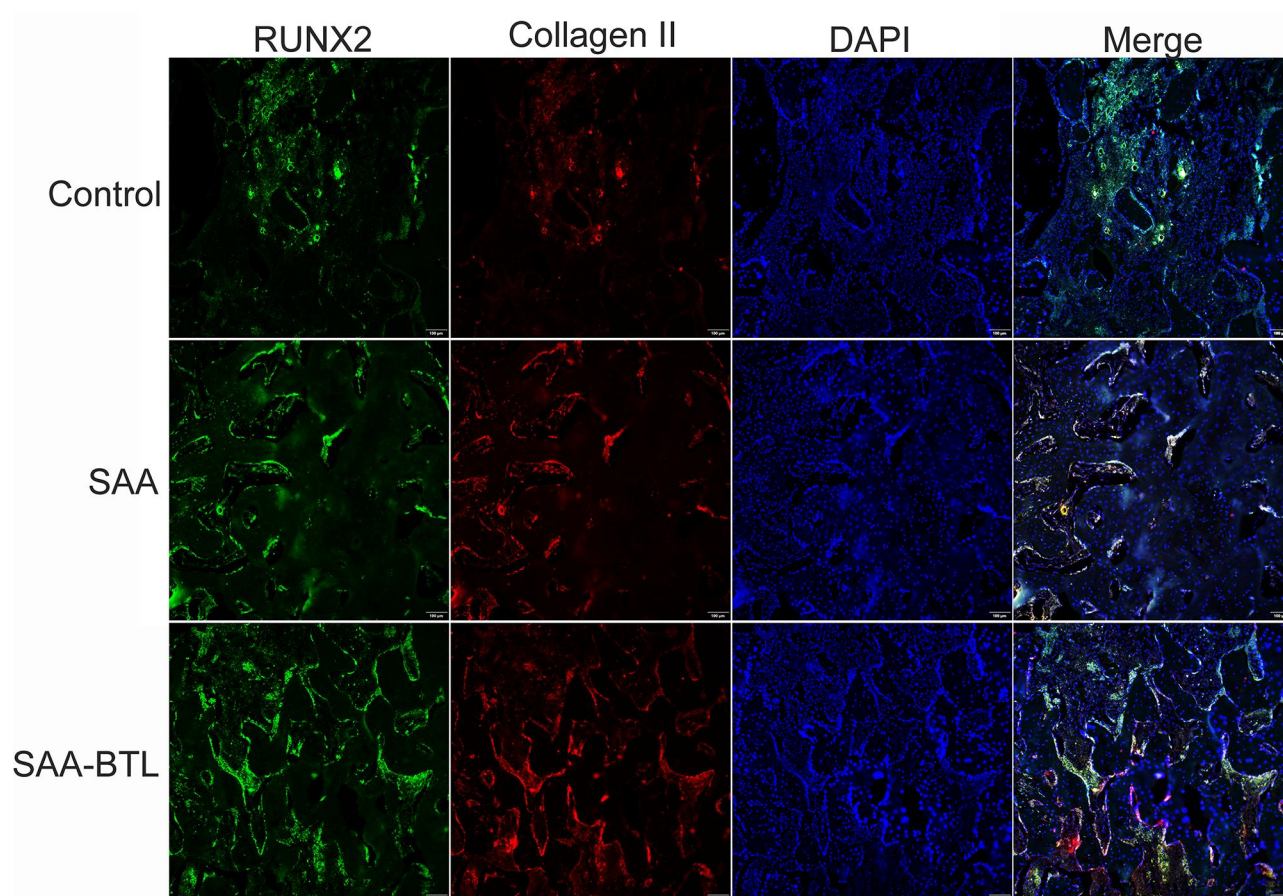


Figure 5 Immunofluorescence analysis of collagen II and RUNX2 expression in fracture calluses at the 4th week post-surgery. RUNX2 and collagen II expression were quantified in sections of the callus. These data are shown in [Figure 7C](#).

saline control ([Figure 8A](#)). The results of both Western blotting and RT-qPCR suggested that SAA treatment significantly increased HDAC3 gene and protein expression in HDAC3 knockdown cells ([Figure 8B](#) and [C](#)). The expression of HDAC3, RUNX2, Col1a1, Col10a1, VEGFA and Sox9 was significantly decreased in ATDC5 cells following siRNA-mediated HDAC3 knockdown. In contrast, the expression of RUNX2, Col1a1, Col10a1, VEGFA, OPG and Aggrecan significantly increased following SAA treatment ([Figure 8C](#)), while the expression of MMP13 significantly decreased.

Based on the *in vitro* and *in vivo* data, we suggest that HDAC3 expression is essential for maintaining endochondral ossification. Therefore, these results suggest that SAA and SAA-BTL enhance the terminal stages of endochondral ossification through an HDAC3-dependent mechanism and promote bone formation via endochondral ossification and vascularisation.

Discussion

In this study, we used pyrophosphorylated cholesterol (cholesterol-PPi's) as bone-targeting ligand for our liposomal formulation of SAA as previously described.¹³ Due to pyrophosphate has a strong binding affinity for hydroxyapatite^{33,34} (the main inorganic constituent of bone), SAA-BTL could bind to the bone via cholesterol-PPi's strong chelation to the bone apatite at different bone surfaces, which significantly improved the effects of SAA. As a novel bone-targeting ligand, pyrophosphate have some advantages compared to bisphosphonates (the most common bone-targeting ligand in current researches).^{35,36} Firstly, pyrophosphate is a safe and biodegradable compound that original exists in human body. It would avoid some limitations associated bisphosphonates. For example, bisphosphonates as antiresorptive agents, long-term use of bisphosphonates has been linked to higher incident rates of osteonecrosis of the jaw (ONJ) and atypical fractures.³⁷ Secondly, pyrophosphate has

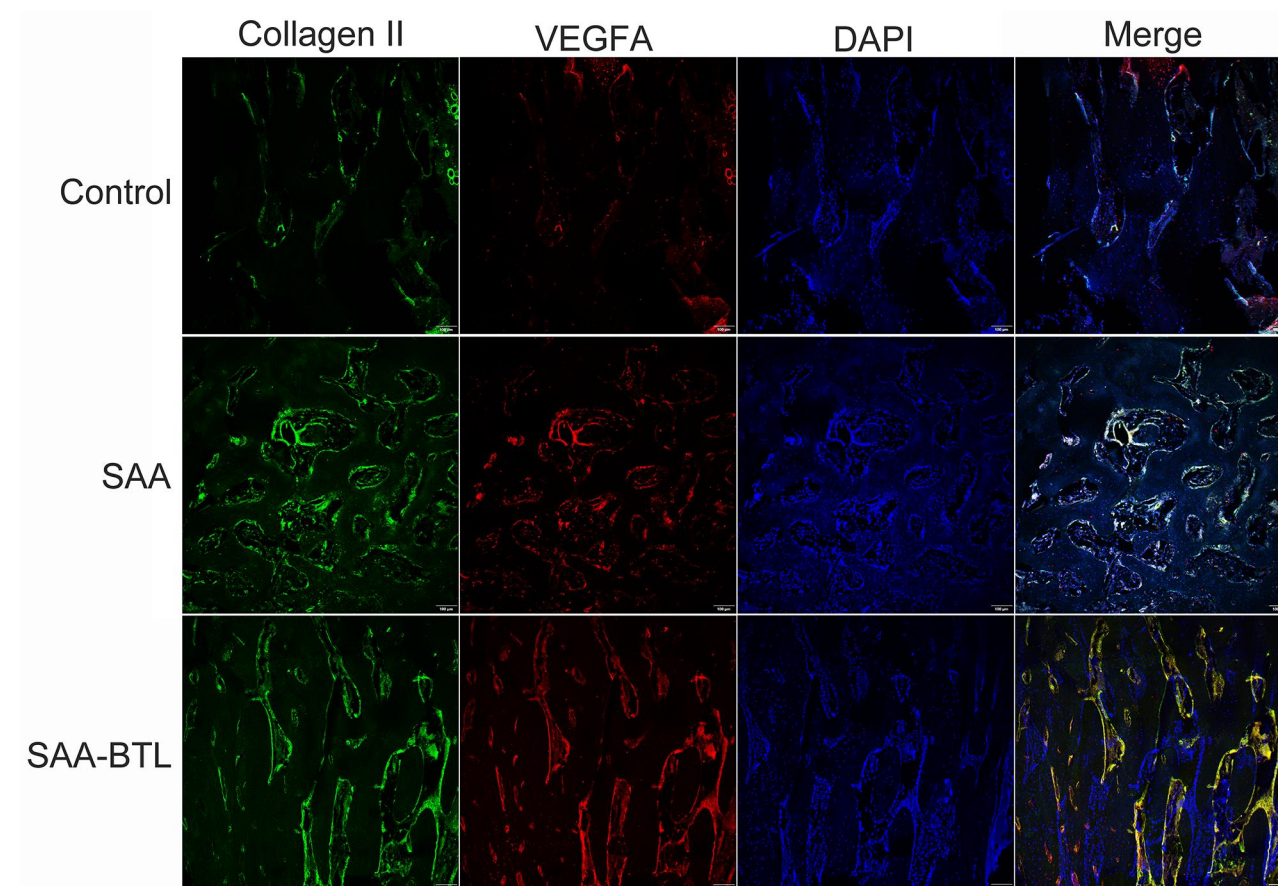


Figure 6 Immunofluorescence analysis of collagen II and VEGFA expression in fracture callus at the 4th week post-surgery. VEGFA and collagen II expression was quantified in sections of the callus. These data are shown in [Figure 7D](#) and [E](#).

no significant pharmacological effects on bone, so it will not hinder the effects of drug that loaded in the liposome. The therapeutic effect of a bisphosphonate-based bone-targeting drug delivery system may be hard to interpret because of the overlapping antiresorptive activities of bisphosphonates. Therefore, bisphosphonates used as ligands for bone-targeted drug delivery in the bone biology field have its shortcomings, especially for chronic conditions. Thirdly, pyrophosphate is low economic cost and easily accessible compared to bisphosphonates. By using cholesterol-PPi's as bone-targeting ligand for our liposomal formulation of SAA, it would significantly improve the efficacy, safety, and stability of the liposome delivery system as the acquired bone targeting property and ζ -Potential from cholesterol-PPi. In this study, results demonstrated that the treatment of SAA-BTL-incorporated collagen sponge significantly improved bone formation in nonunion defect. SAA-BTL and collagen sponge combined strategy provide both osteoinduction and osteoconduction effects in the nonunion healing process, improving the therapeutic efficacy of intervention on nonunion fractures.

Chondrocyte hypertrophy followed by cartilage matrix degradation and vascular invasion, characterised by the expression of Col10a1, MMP13, and VEGF, is a series of important procedures in endochondral ossification during skeletal growth.³⁸ A previous study has showed that HDAC3-dependent signalling in chondrocytes supports the maintenance of matrix degradation and vascular invasion of endochondral ossification.²²

In order to reveal the underlying mechanism of action of SAA in nonunion healing process, a chondrogenic cell line (ATDC5) was used as a cell model because ATDC5 cells show a sequential transition of phenotype in vitro, encompassing stages from mesenchymal condensation to calcification. Chondrocyte calcification in vitro can mimic the endochondral ossification in the healing process in vivo. Endochondral ossification is one of the most important steps in fracture healing process. ATDC5 cell line has been used for endochondral ossification research in a previous study.²² In this study, our data demonstrated that knockdown of HDAC3 in ATDC5 cells delayed

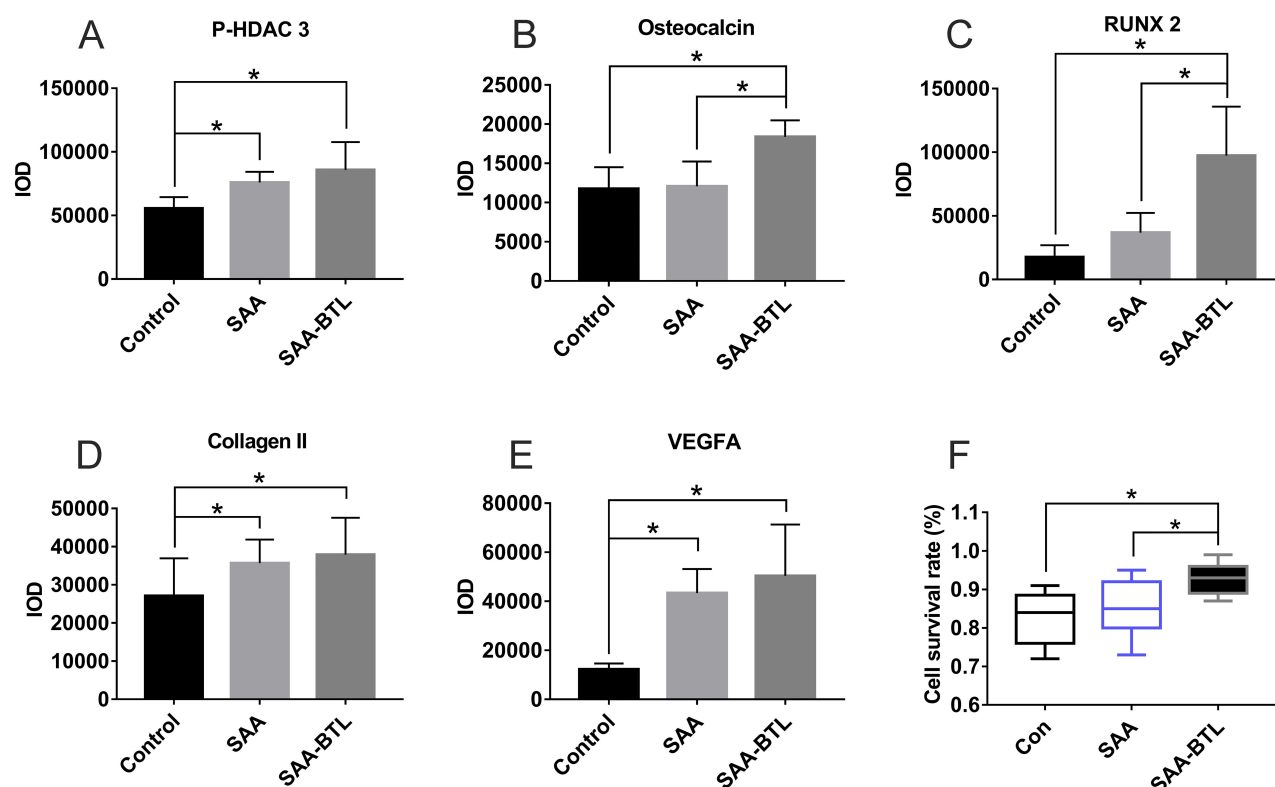


Figure 7 (A–E) Quantitative data from immunofluorescent analysis of P-HDAC3, osteocalcin, RUNX2, collagen II, and VEGFA expression in fracture calluses at the 4th week post-surgery (N=5) **(F)** Quantitative data from the live/dead analysis of ATDC 5 cells seeded on SAA/SAA-BTL-incorporated collagen sponges for 24 h of incubation. * $p < 0.05$.

ossification, altered terminal chondrocyte hypertrophy and ossification, and disrupted angiogenesis. However, SAA treatment significantly increased HDAC3 expression and stimulated expression of Col10a1 and VEGFA while suppressing MMP13 expression in HDAC3 knockdown ATDC5 cells. In addition, we have shown that SAA treatment increased the expression of bone formation markers (RUNX2, Col1a1, and OPG) in HDAC3 knockdown ATDC5 cells. In this study, we used our previously developed BTL liposomes, which act as drug delivery vehicles that precisely target the bones and provide controlled-release within the skeleton system for prolonged periods. Due to the bone targeting property of the liposome, the liposome would release from collagen sponge and target the adjacent bone surfaces. SAA-BTL could be taken up by multiple cell types adjacent to bone surface (including BMSCs, osteoblasts, osteoclasts, chondrocytes, periosteal cells, fibroblasts, macrophages, etc.) and could even be taken up by cells in the bone lacuna.¹³ In this process, the most important cells are MSCs, which are recruited to the bone defect and which may also uptake the liposome or which may be affected by SAA released from the liposome.

Conversely, SAA-BTL was incorporated into the collagen sponge, which has high biocompatibility and provides a scaffold framework to accommodate tissue repair cells (bone marrow mesenchymal stem cells (BMSCs), chondrocytes, osteoblast, osteoclast, endothelial cells, etc.). From our animal studies, we found that SAA and SAA-BTL activated P-HDAC3 expression and increased the expression of VEGFA, collagen II, RUNX2, and osteocalcin in radial non-union fracture region, thereby stimulating bone formation. RUNX2, osteocalcin, and VEGFA are the key markers of endochondral ossification, which reveals changes in transformation of cartilage callus to bony callus. In addition, histological analysis revealed higher bone and lower chondrocyte areas in the nonunion region of rabbits treated with SAA-BTL compared to those in the rabbits treated with control, indicating that endochondral ossification turnover from cartilage to bone was accelerated following SAA-BTL treatment. A previous study revealed that chondrocytes from HDAC3 CKO_{OSX} mice show increased hypertrophy but the cartilaginous matrix production of cells is significantly impaired.³⁹ A reduction in the mineral-to-matrix ratio and an increased carbonate-to-phosphate ratio in HDAC3-

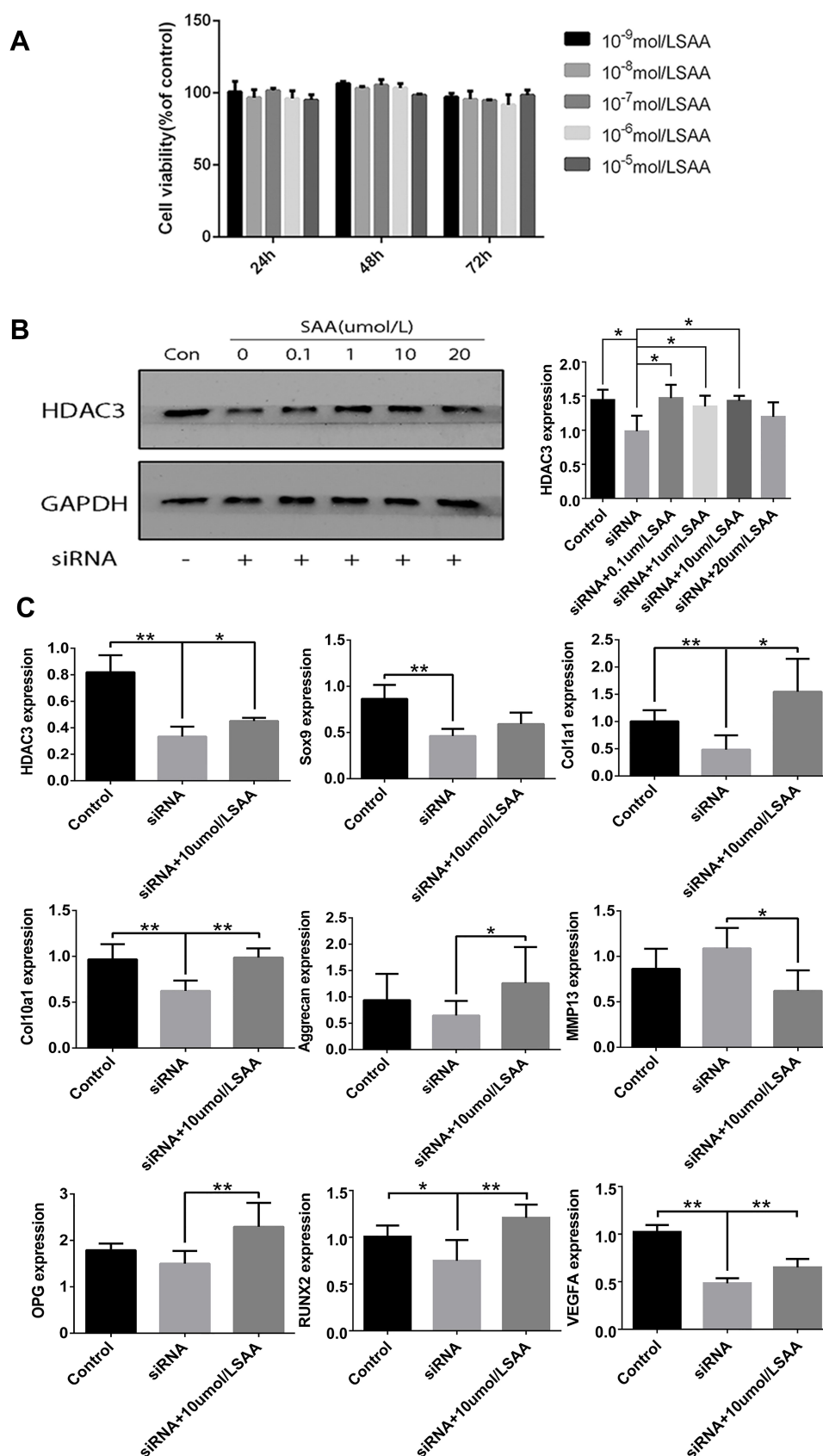


Figure 8 The impact of SAA treatment on ATDC5 cells. (A) Cell viability of ATDC5 cells treated with SAA for 24, 48, and 72h. (B) HDAC3 protein expression in ATDC5 HDAC3-knockdown cells treated with SAA for 48h. (C) RT-qPCR analysis of gene expression in the ATDC5 HDAC3-knockdown cells treated with SAA for 72h. * $P < 0.05$, ** $P < 0.01$.

insufficient animals resulted in poor bone quality, which increases the risk of fracture. These data suggest that HDAC3-insufficiency induces deficient endochondral ossification. Therefore, our results are in agreement with those of previous findings. HDAC3 conditional knockout mice have also demonstrated delayed angiogenesis, progressively decreased trabecular and cortical bone mass, bone mineral density, reduced material properties, and increased risk of fractures, all of which support our hypothesis.^{22,40} HDAC3 is essential for the maintenance of genome stability and chromatin structure.^{41,42} HDAC3 supports functions of multiple cells in the fracture repair process, including BMSCs, osteoblasts, osteocytes, and fibroblasts.²⁷ Inefficient differentiation of osteoblasts was identified in HDAC3 CKO_{OCN} cells. The loss of HDAC3 in committed osteoblasts and osteocytes impaired bone formation and bone-specific gene expression, induced DNA damage, and resulted in bone loss.⁴⁰ HDAC3 knockout embryonic fibroblasts (MEFs) caused DNA damage that ultimately induced cell cycle arrest. These results suggest that HDAC3 may control cell-cell crosstalk between chondrocytes and osteoblasts, BMSCs, and vascular endothelial cells, which is required for the integrated formation of cartilage, blood vessels, and bone during the fracture healing process.

Earlier reports have shown that SAA stimulates osteogenesis and depresses adipogenesis in BMSCs both in vitro and in vivo.^{15,16,43} Specifically, SAA attenuates the impairment of bone formation, bone loss, and bone quality deterioration elicited by glucocorticoid-mediated KLF15/WNT signalling and suppresses the glucocorticoid-induced oxidative stress and subsequent cell apoptosis associated with the KLF15/p66Shc signalling cascade.¹⁷ Yang et al confirmed the protective effects of SAA on oxidative stress and its signalling pathways in osteoblastic differentiation. However, the mechanism of SAA in the prevention and treatment of fracture healing disorders is not well understood. Our previous study confirmed that SAA-BTL accelerates fracture healing and improves biomechanical properties in prednisone-induced femur fractures in a murine model of delayed healing. In this study, the large bone defect-induced nonunion rabbits were treated with SAA/SAA-BTL-incorporated collagen sponges, which induced significant bone formation and accelerated endochondral ossification in the animal model. These processes were shown to be regulated by HDAC3 expression and they could provide a roadmap for improving the therapeutic efficacy of intervention strategies for nonunion fractures.

Conclusion

In summary, it was confirmed that SAA and SAA-BTL actively stimulate osteogenesis and chondrogenesis during fracture healing and accelerate the ossification turnover from cartilage to bone through the regulation of HDAC3-mediated endochondral ossification. Therefore, this study provides an effective strategy and target for nonunion therapy.

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Author Contributions

All authors meet the criteria for authorship. All authors made substantial contributions to conception and design of the study, acquisition of data, and analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; gave final approval of the version to be published; and agree to be accountable for all aspects of the work.

Disclosure

The authors declare no conflicts of interest.

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