

Research Article

Extracellular regulated kinase 5 mediates osteoporosis through modulating viability and apoptosis of osteoblasts in ovariectomized rats

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Postmenopausal osteoporosis is a common condition characterized by the increase and activation of osteoclasts. The present study aimed to investigate the effects of extracellular signal-regulated kinase (ERK) 5 (ERK-5) on postmenopausal osteoporosis by regulating the biological behaviors of osteoblasts. Sprague–Dawley (SD) rats were ovariectomized to develop an osteoporosis model. A lentivirus packaging system was employed to generate lentiviruses capable of up- or down-regulating the expression of ERK-5 in ovariectomized rats. The femoral biomechanical properties, bone mineral density (BMD), contents of calcium (Ca), phosphorus (P) and alkaline phosphatase (ALP) and bone turnover markers in rats, as well as viability, cycle and apoptosis of osteoblasts and ALP activity in osteoblasts were measured in the ovariectomized rats so as to explore the functional significance of ERK-5 in postmenopausal osteoporosis. The femoral mechanical strength of ovariectomized rats was enhanced by overexpression of ERK-5. Meanwhile femoral BMD, and bone metabolism were increased, and bone turnover normalized in the ovariectomized rats when ERK-5 was overexpressed. Lentivirus-mediated ERK-5 overexpression in osteoblasts was observed to inhibit osteoblast apoptosis, and promote viability, accompanied with increased ALP activity. Taken together, ERK-5 could decelerate osteoblast apoptosis and improve postmenopausal osteoporosis by increasing osteoblast viability. Thus, our study provides further understanding on a promising therapeutic target for postmenopausal osteoporosis.

Introduction

Osteoporosis is a chronic progressive disease characterized by the deterioration of bone microstructure, low bone mass, bone fragility and increasing risk of fracture [1,2]. Osteoporosis often exhibits no obvious symptoms unless it deteriorates into fractures with minimal trauma or without trauma under some circumstances [3]. Fractures caused by osteoporosis occur every 3 s and fractures at the spine and hip result in substantial mortality and morbidity worldwide [4]. The increase in life expectancy makes women live longer in menopause, without naturally producing estradiol and progesterone, resulting in increasing incidence of osteoporosis [5]. At present, therapeutic options for women diagnosed with osteoporosis include osteoporosis-specific medication, lifestyle interventions, as well as increased calcium (Ca) and vitamin D intake [6]. However, numerous patients suffering from osteoporosis-caused fractures often fail to be correctly diagnosed which results in failure to receive valid therapies admitted by Food and Drug Administration [3]. The disability and mortality instigated by osteoporosis greatly affect the life quality of the aging population, particularly in patients over 65 even though the lifestyle changes could lower the osteoporosis risks [7]. Additionally, the development of novel treatment methods as well as improvement to existing osteoporosis treatment methods has been largely limited because of the difficulties encountered in establishing drugs capable of influencing the progression of the disease [2]. Due to the limitations of

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Table 1 The treatment of rats in different groups

Group	<i>n</i>	Treatment
Sham	10	Sham-operated rats with ovaries exposed but not resected
OVX	10	Ovariectomized rats with removal of ovaries injected with PBS
OVX + NC	10	Ovariectomized rats with removal of ovaries, injected with Lentivirus-GFP
OVX + ERK-5 shRNA	10	Ovariectomized rats with removal of ovaries, injected with Lentivirus-ERK-5-shRNA
OVX + ERK-5 overexpression	10	Ovariectomized rats with removal of ovaries, injected with Lentivirus-ERK-5-overexpression

Abbreviations: *n*, number; OVX, ovariectomized rat; shRNA, short hairpin RNA.

present therapies, attempts to develop improved treatment options are being pursued. Toward this, we introduce extracellular signal-regulated kinases (ERKs)-5 (ERK-5) into the study of osteoporosis-related factors, with the view of providing new insight for the development of osteoporosis intervention strategies.

Mitogen-activated protein kinase (MAPK) signaling cascades form a complicated signaling pathway network and regulate the genes involved in a wide variety of cellular processes, including cell proliferation, differentiation, apoptosis and synaptic plasticity by acting as a significant part in the transduction of extracellular signals to cytoplasmic and nuclear effectors [8]. As a member of the MAPK family, ERK-5 has been reported to be involved in cell proliferation, survival, connexin-43 phosphorylation and gap junctional intercellular communication modulation [9,10]. MAPK has been reported to be up-regulated in the ovariectomy-induced bone loss and is greatly involved in the regulation of osteogenesis [11]. Osteoblasts play a crucial role in growth and maintenance of the bone, whose dysfunction due to disordered substrate availability has been suggested to lead to osteoporotic fractures [12]. Based on the aforementioned exploration of literature, we speculate that there are relationships between ERK-5 and osteoporosis. Thus, we conducted the present study to explore mediatory roles of ERK-5 in the properties of bone tissues and functions of osteoblasts including proliferation and apoptosis.

Materials and methods

Model establishment and infection

A total of 60 nonparous healthy female Sprague–Dawley (SD) rats (weighing 200–280 g) were purchased from SLAC Laboratory Animal Co., Ltd, Shanghai, China. All the rats were raised in a well-ventilated clean animal room (21–23°C, humidity of 60 ± 5%) with free access to food and water, in 12/12-h light–dark cycle. Ten rats were randomly selected as the sham group (sham-operated rats). For the sham-operated rats, ovaries were exposed but not resected [14]. The remaining 50 rats were used to establish an ovariectomized female rat model with osteoporosis [15]. The rats were anesthetized using 2% pentobarbital sodium with a 1-cm incision made at the junction of 1 cm below the ventral costal margin and 1 cm either side of the spinal cord. The bilateral ovaries were subsequently ligatured and removed. The rats were then intraperitoneally injected with 400000 units of penicillin after operation to prevent infection. The rats that died during the operation were removed from the study. Ultimately, 44 rats were successfully ovariectomized and 40 were randomly selected and divided into four groups.

Eight weeks after operation, Lentiviral-ERK-5-overexpression vector, Lentiviral-ERK-5-shRNA vector and empty vector Lentiviral-GFP (Shanghai Genechem Gene Tech Co., Ltd, Shanghai, China) were injected into the ovariectomized rats with the usage of Entranster™-*in vivo* infection reagent (Engreen Biosystem, Co., Ltd, Beijing, China). Specifically, the rats were anesthetized using 2% pentobarbital sodium (0.5 mg/kg) via intraperitoneal injection. After anesthesia, the surgical site was sterilized using iodophor and lentiviral injection was performed at the either side of spine with a total volume of 20 µl. The rats were subsequently assigned into sham group (sham-operated rats), OVX group (ovariectomized rats injected with PBS), OVX + negative control (NC) group (ovariectomized rats injected with Lentivirus-GFP vector), OVX + ERK-5 shRNA group (ovariectomized rats injected with Lentivirus-ERK-5-shRNA vector), and OVX + ERK-5 overexpression group (ovariectomized rats injected with Lentivirus-ERK-5-overexpression vector), with ten rats in each group (Table 1). The flow chart of experimental design is shown in Supplementary Figure S1.

Western blot assay

Total proteins from tissues and cells were extracted using high-efficiency Radio-immunoprecipitation Assay lysis buffer (R0010, Solarbio Co., Ltd, Beijing, China) in strict accordance with the provided instructions. After lysis at 4°C

for 15 min, the cells were centrifuged at 12000 rpm for 15 min, after which the protein concentration in the extracted supernatant was determined using a bicinchoninic acid (BCA) kit (20201 ES76, Yeasen Biotech CO., Ltd., Shanghai, China). After protein separation using polyacrylamide gel electrophoresis, the proteins were transferred on to a polyvinylidene fluoride membrane via the wet transfer method, and blocked with 5% bovine serum albumin (BSA) at room temperature for 1 h. The membrane was incubated with diluted primary antibody to ERK (ab196609, 1:1000) overnight at 4°C on a shaker. The membrane was then washed for three times (5 min each time) with Tris-Buffered Saline with Tween (TBST), after which Horseradish peroxidase-labeled secondary antibody was added and diluted at room temperature for 1 h. The membrane was then washed three times with TBST (5 min each time), followed by developing. ImageJ 1.48u software (National Institutes of Health, NY, U.S.A.) was applied for protein quantification analysis by calculating the ratio of the gray value of each protein to the gray value of the internal reference glyceraldehyde-3-phosphate dehydrogenase (GAPDH) (ab9485, 1:2500).

Detection of bone mineral density

Three rats in each group were anesthetized 8 weeks after operation and bone mineral density (BMD) was measured using dual energy X-ray absorptiometry (DEXA) with different dosages of X-ray as the radioactive source. A DPX-L (Lunar, Madison, WI, U.S.A.) was adopted to measure the BMD in order to confirm that the osteoporosis model had been successfully constructed (BMD declined if the model was successful). After the experiment (16 weeks after operation), the rats (three in each group) were killed. Next, the left and right femurs were peeled off, with the spinous process and transverse process cut as well as removal of the muscle tissues. The right femur was selected for BMD determination using DEXA method (unit: g/cm²).

Hematoxylin-Eosin staining

After the rats were killed, the left femur of rats (from the samples collected before BMD determination) was collected. The bone tissues were fixed with 4% paraformaldehyde and dehydrated with gradient alcohol, immersed in wax and embedded to make bone tissue sections (with thickness of 5 µm). The tissues were subsequently conventionally dewaxed, stained with Hematoxylin-Eosin (HE), and then stained by Hematoxylin for 10 min. Next, the tissues were differentiated with 1% hydrochloric acid alcohol, dehydrated conventionally with gradient alcohol and counterstained with Eosin for 2 min. After dehydration, transparency and sealing with resin, the morphological changes were analyzed under a microscope (CX31, Olympus Optical Co., Ltd, Tokyo, Japan). Serial sections were selected as the region of interest starting at 3.5 mm away from the growth plate of distal femur in order to analyze the trabecular bone. The representative images of the cortical and trabecular bone structures were visualized using the medical image analysis system (BI-2000, Taimeng, Chengdu TaiMeng Technology Co., Ltd., Chengdu, China). Trabecular bone regions were recorded by computer-aided software.

Detection of Ca, phosphorus and alkaline phosphatase contents

A week after transfection, blood from rats' abdominal aorta was obtained and placed for 30 min, and centrifuged at 1118×g for 20 min at 4°C to separate serum. The serum was stored for subsequent experimentation. The automatic biochemical analyzer (Beckman 700, Fullerton, CA, U.S.A.) was employed to detect the contents of Ca, phosphorus (P) and alkaline phosphatase (ALP) in rat's blood according to the instructions of Ca, P and ALP kit (Nanjing Jiancheng Bioengineering institute, Nanjing, China).

Enzyme-linked immunosorbent assay

The abdominal aorta blood and urine were collected 1 week after the rats had been infected with lentiviral vectors. The blood was placed for 30 min and centrifuged at 2500 rpm at 4°C for 20 min after which the serum was stored. The urine was separated and stored for later use. The experiment was performed as per the instructions of the Enzyme-linked immunosorbent assay (ELISA) kit (Nanjing Jiancheng Institute of Bioengineering, Nanjing, China). In brief, 100 µl of samples were added into the reaction plate followed by construction of a standard curve. A total of 100 µl sample was added into the reaction well at 37°C for 90 min. After washing, 100 µl of the working solution of biotinylated antibody was added at 37°C for 60 min, and 100 µl of the working solution of enzyme binding reagent (stored avoiding exposure to light) was added at 37°C for 30 min. Next, 100 µl of substrate was added to the plate at 37°C for 15 min under conditions void of light. The reaction was terminated following the addition of a stopping solution. Optical density (OD) value was detected using universal microplate reader (450, Bio-Rad, Inc., Hercules, CA, U.S.A.) at 450 nm within 3 min. The standard curve was drawn based on the OD values. The levels of urinary deoxyypyridinoline (DPD), serum osteopontin (OPN; ng/ml) and serum osteocalcin (OCN; ng/ml) in rats were then evaluated. The

urinary DPD concentration was expressed as the ratio of urinary DPD to the concentration of Cr (nanomoles to micromoles) [16].

Three-point bending test

Eight weeks after infection with lentiviral vector, rats (three in each group) were killed. The damaged portion of the metaphyseal part in the femur was then removed and placed on two saddle-shaped stents with a span of 20 mm. The three-point bending test was applied to the distal third of femoral shaft using Shimadzu universal testing machine. The saddle indenter attached to the sensor was used to apply pressure on the midpoint of the two saddle-shaped stent sections at a loading rate of 1 mm/min. The trial ended with femoral fracture. The experimental data were analyzed using TRAPEZIUM2 analysis software to obtain mechanical structural parameters (maximum load, breaking load, structural stiffness, energy absorption, maximum bending moment) and material mechanical parameters (elastic modulus, ultimate strength, breaking strength, maximum strain, breaking strain).

Cell culture, transfection and grouping

The cleaned skull of the ovariectomized rats was detached with 0.25% trypsin, crushed into pieces, and then detached with 0.1% collagenase for 40 min. Next, the osteoblasts were collected after centrifugation. The collected osteoblasts were cultured in Dulbecco's modified Eagle's medium (DMEM) (Gibco, Gaithersburg, MD, U.S.A.) containing 10% fetal bovine serum (FBS) (HyClone, South Logan, UT, U.S.A.) at 37°C with 5% CO₂. After detachment with 0.25% trypsin (Gibco, Gaithersburg, MD, U.S.A.), the cells were pipetted into a single cell suspension in DMEM containing 10% FBS. After routine passage had been performed, the osteoblasts in the logarithmic growth phase were seeded into six-well plates at a density of 3×10^5 cells/well and transfected after the cells had grown to 80–90% confluence. The osteoblasts were transfected with NC plasmid, ERK-5 siRNA (sc-35340, Santa Cruz Biotechnology, Inc, Santa Cruz, CA, U.S.A.) or ERK-5 overexpression vector using transfection reagent (sc-45064, Santa Cruz Biotechnology, Inc, Santa Cruz, CA, U.S.A.). Liquid A was 2–8 μ l siRNA + 100 μ l transfection medium; liquid B was 6 μ l transfection reagent + 100 μ l transfection medium. The solutions A and B were mixed and incubated for 30 min. A total of 0.8 ml of transfection medium was then added and mixed for subsequent experiments. A volume of 2 ml transfection medium was used to wash the osteoblasts twice, after which the prepared liquid was added and cultured in an incubator for 6 h. An additional 1 ml medium containing two-times the serum and antibiotics was added and cultured for 12–48 h.

3-(4,5-dimethyl-2-thiazolyl)-2,5-diphenyl-2-H-tetrazolium bromide assay

The osteoblasts were treated with trypsin and collected in a centrifuge tube. The cells were diluted at a density of 1×10^3 cells/100 μ l and seeded into a 96-well plate. After cell culture for 24 h, 20 μ l fresh 3-(4,5-dimethyl-2-thiazolyl)-2,5-diphenyl-2-H-tetrazolium bromide (MTT) solution (5 mg/ml, tetramethylazole, Sigma–Aldrich Chemical Company, St. Louis, BRL, U.S.A.) was added to each well and incubated for 4 h at 37°C. After the medium was discarded, 150 μ l of dimethylsulfoxide (DMSO) (Sigma–Aldrich Chemical Company, St. Louis, BRL, U.S.A.) was added. Four replicate wells were set for each group. An OD value of 490 nm was measured on a microplate reader (450, Bio-Rad Laboratories, Hercules, CA, U.S.A.).

Flow cytometry

The cells in each group were cultured for 24 h and then detached with 0.25% trypsin. Medium with serum was added to stop digestion. Pre-cooled 70% ethanol was then added in order to fix the cells for 30 min, with the cells then collected. After PBS washing, the cells were stained with 1% propidium iodide (PI) containing RNase for 30 min and washed twice with PBS to remove the PI. The volume was adjusted to 1 ml with PBS. The cell cycles were examined using a BD-Aria FACS Calibur flow cytometer (model FACS Calibur, Beckman Coulter Inc., U.S.A.). The experiment was conducted repeatedly three times in triplicates.

After culturing for 24 h, the cells were detached with trypsin without ethylenediaminetetraacetic acid (EDTA) and then collected. Annexin-V-FITC/PI solution was made with Annexin-V-FITC, PI and HEPES buffer solutions at a ratio of 1:2:50 in accordance with the instructions of the Annexin-V-FITC Apoptosis Detection Kit (Cat No. C1065, Beyotime Biotechnology Co., Shanghai, China). Cells (1×10^6) were resuspended with 100 μ l of dyeing and mixed by shaking. A volume of 1 ml HEPES buffer solution was added following a 15-min period of incubation, after which the cells were mixed by shaking. Flow cytometry was employed for cell apoptosis detection.

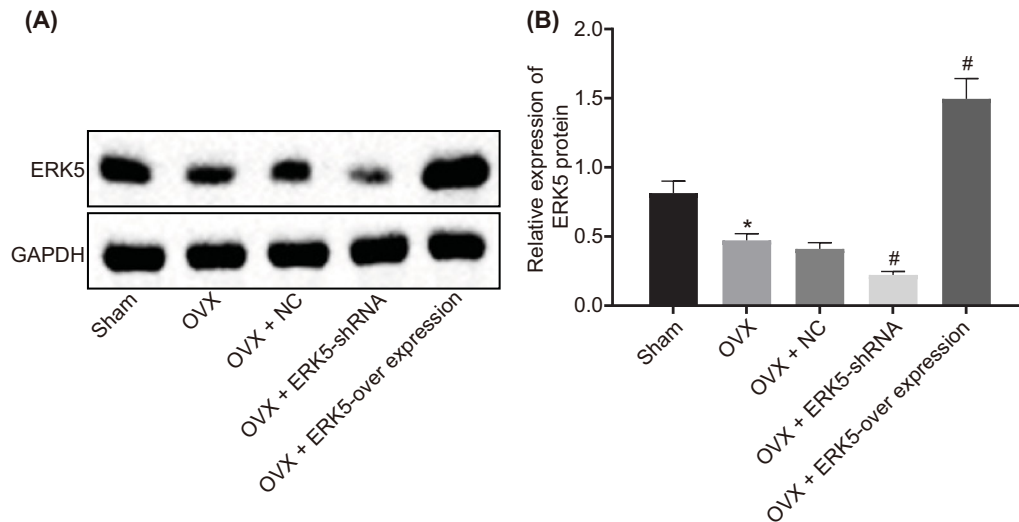


Figure 1. The expression of ERK is decreased in the bone tissues of ovariectomized rats

Western blots (A) and protein expression (B) of ERK normalized against GAPDH in the sham-operated rats, ovariectomized rats without infection or ovariectomized rats infected with Lentivirus-GFP vector, Lentivirus-ERK-5-shRNA vector or Lentivirus-ERK-5-overexpression vector. * $P < 0.05$ vs. the sham group; # $P < 0.05$ vs. the OVX group. Abbreviations: OVX, ovariectomized rat; shRNA, short hairpin RNA.

Detection of ALP activity of osteoblasts

The osteoblasts were collected into centrifuge tubes following trypsin treatment, after which the cells were diluted to a density of 1×10^4 cells/ml and seeded into 24-well plate. After the cells were cultured for 24 h, the medium was replaced with serum-free medium, with the nutrient fluid then pipetted. After the addition of 1 ml of 0.1% Triton-100 into each well and reacting for 30 min, 50 μ l matrix solution and 50 μ l buffer solution were added into each well, thoroughly mixed and incubated at 37°C for 15 min. The OD value of each well was measured at 520 nm with microplate reader to obtain its content. The ALP activity of osteoblast in each group after 7 and 14 days of culture was detected using the aforementioned method.

Statistical analysis

Statistical analysis was performed using SPSS 21.0 software (IBM Corp. Armonk, NY, U.S.A.). Measurement data were expressed as the mean \pm standard deviation (S.D.). Measurement data obeying the normal distribution between two groups were assessed using a *t* test while comparison between multiple groups was analyzed using one-way analysis of variance (ANOVA). $P < 0.05$ was considered to indicate statistical significance.

Results

ERK-5 improves the biomechanical properties of ovariectomized rats' femur

The expression of ERK-5 in the bone tissues was detected using Western blot analysis to explore interference and over-expression efficiency of ERK by lentiviral vectors. The results obtained indicated that compared with sham group, the expression of ERK in bone tissue of the OVX group was markedly decreased. Compared with the OVX and OVX + NC groups, the expression of ERK-5 was notably reduced in OVX + ERK-5 shRNA group, but increased in OVX + ERK-5 overexpression group (Figure 1). Compared with the sham group, the mechanical structural parameters (including maximum load, breaking load, structural stiffness, energy absorption, maximum bending moment) and material mechanical parameters (including elastic modulus, ultimate strength, breaking strength) in the OVX, OVX + NC, OVX + ERK-5 shRNA, OVX + ERK-5 overexpression groups considerably diminished (all $P < 0.05$). Besides, compared with the OVX + NC group, the mechanical structural and material mechanical parameters significantly decreased in the OVX + ERK-5 shRNA group while increased in the OVX + ERK-5 overexpression group (all $P < 0.05$).

Table 2 ERK-5 overexpression enhances biomechanical property of rats' femurs

Group	sham	Ovariectomized rat			
		OVX	OVX + NC	OVX + ERK-5 shRNA	OVX + ERK-5 overexpression
Maximum loads (N)	117.68 ± 5.29	94.59 ± 5.26*	94.83 ± 7.81*	80.06 ± 6.45*†	105.37 ± 6.30*†
Breaking load (N)	96.73 ± 5.34	70.09 ± 5.86*	69.58 ± 7.66*	52.11 ± 4.72*†	83.76 ± 5.49*†
Energy absorption (N.mm)	82.41 ± 5.87	52.56 ± 7.12*	51.34 ± 5.94*	32.57 ± 3.62*†	69.44 ± 6.36*†
Structural stiffness (N.mm ⁻¹)	199.57 ± 11.26	160.56 ± 9.18*	153.80 ± 10.67*	112.92 ± 6.59*†	177.66 ± 10.84*†
Maximum bending moment (N.mm)	711.5 ± 51.35	548.81 ± 63.12*	529.46 ± 44.13*	450.68 ± 27.62*†	634.07 ± 39.72*†
Elasticity modulus (N.mm ⁻¹)	5997.10 ± 171.30	4833 ± 121.8*	4736.50 ± 153.90*	3655.80 ± 131.50*†	5367.20 ± 158.40*†
Ultimate strength (N.mm ⁻²)	176.43 ± 11.91	134.21 ± 13.52*	129.76 ± 14.21*	108.82 ± 9.83*†	155.24 ± 13.32*†
Breaking strength (N.mm ⁻²)	168.61 ± 13.33	119.63 ± 10.46*	117.12 ± 14.20*	96.71 ± 8.81*†	140.35 ± 13.42*†
Maximum strain (%)	5.65 ± 0.56	2.71 ± 0.31*	2.70 ± 0.25*	1.97 ± 0.57*†	3.54 ± 0.34*†
Breaking strain (%)	7.96 ± 0.90	4.57 ± 1.1*	4.55 ± 0.75*	3.30 ± 0.35*†	5.84 ± 1.30*†

Abbreviation: ERK-5 siRNA, ERK-5 small interfering RNA.

*, $P < 0.05$ vs. the normal group.

†, $P < 0.05$ vs. the postmenopausal osteoporosis group.

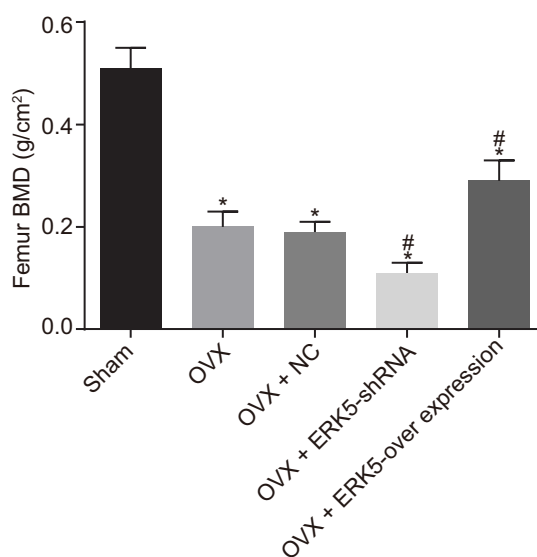


Figure 2. The femoral BMD in ovariectomized rats is increased following the overexpression of ERK, as detected using DEXA

$n=10$. * $P < 0.05$ vs. the sham group; # $P < 0.05$ vs. the OVX group. Abbreviations: OVX, ovariectomized rat; shRNA, short hairpin RNA.

The aforementioned findings suggested that the biomechanical properties in ovariectomized rats decreased. Furthermore, the overexpression of OVX + ERK-5 could improve the biomechanical properties of ovariectomized rats' femur while the biomechanical properties reduced in the event of ERK-5 expression silencing (Table 2).

ERK-5 increases femoral BMD of ovariectomized rats

The BMD of the rats in each group was measured. The results revealed that compared with the sham group, the BMD of rats' femur in the OVX, OVX + NC, OVX + ERK-5 shRNA, OVX + ERK-5 overexpression groups declined obviously ($P < 0.05$). Compared with the OVX + NC group, the BMD of rats' femur in the OVX + ERK-5 shRNA group decreased while increased in the OVX + ERK-5 overexpression group (Figure 2). The obtained results demonstrated that ERK-5 overexpression could increase the femoral BMD of ovariectomized rats by regulating osteoblast function.

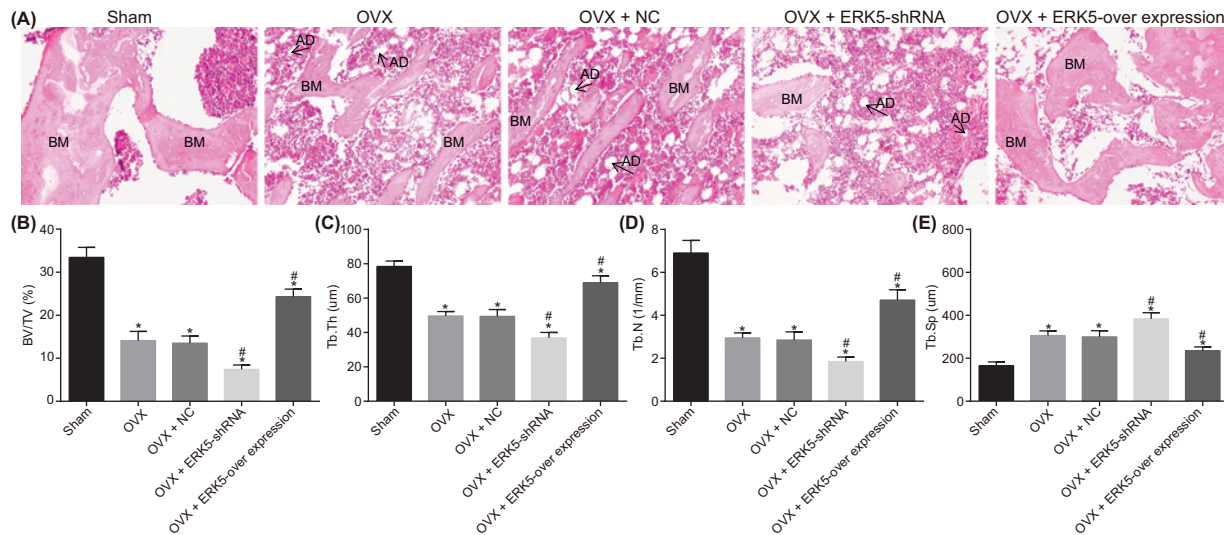


Figure 3. Morphological changes of the femur tissues were affected by overexpression of ERK

(A) The morphological changes in femur tissues observed under optical microscope after HE staining ($\times 200$); bone trabecular area (B), thickness (C), density (D) and gap (E) in sham-operated rats, ovariectomized rats without infection or ovariectomized rats infected with Lentivirus-GFP vector, Lentivirus-ERK-5-shRNA vector or Lentivirus-ERK-5-overexpression vector. $*P < 0.05$ vs. the sham group; $\#P < 0.05$ vs. the OVX group. $n = 10$. Abbreviations: AD, adipocyte; BM, bone matrix; OVX, ovariectomized rat; shRNA, short hairpin RNA.

ERK-5 affects the femoral morphology in the ovariectomized rats

The morphology of the osteoporosis rats' femur was analyzed using HE staining, the results of which revealed that, compared with the sham group, the trabecular bone of the OVX, OVX + NC, OVX + ERK-5 shRNA, OVX + ERK-5 overexpression groups was obviously slender, the coloration was faint, the margin was rough, the structure integrity was poor, the fragment appeared, the number of the trabecular was significantly reduced, and the interval obviously increased ($P < 0.05$). Compared with the OVX + NC group, trabecular was more slender, with worsened structural integrity, significantly reduced trabecular number, the interval was significantly increased and medullary cavity was broadened in the OVX + ERK-5 shRNA group ($P < 0.05$); while the trabecular width and thickness were increased, the interval was smaller, the number increased, the arrangement was regular and structure was completed, neat with smaller marrow cavity in OVX + ERK-5 overexpression group ($P < 0.05$) (Figure 3). The aforementioned results provided evidence confirming that ERK-5 could improve the morphology of ovariectomized rats' femur.

ERK-5 increases bone metabolism in ovariectomized rats

The contents of Ca, P and ALP were determined using an automatic biochemical analyzer. The contents of Ca, P and ALP in the OVX, OVX + NC, OVX + ERK-5 shRNA, OVX + ERK-5 overexpression groups were notably lower than those in the sham group (all $P < 0.05$). Compared with the OVX + NC group, Ca, P, ALP contents in the OVX + ERK-5 shRNA group were notably decreased ($P < 0.05$) while those in the OVX + ERK-5 overexpression group were significantly increased ($P < 0.05$) (Figure 4). The results obtained indicated that ERK-5 could mediate bone metabolism levels in ovariectomized rats.

ERK-5 normalizes bone turnover in ovariectomized rats

The contents of bone turnover markers including DPD, OCN and OPN were determined by ELISA. The ELISA results revealed that the contents of DPD, OCN and OPN in the OVX, OVX + NC, OVX + ERK-5 shRNA, OVX + ERK-5 overexpression groups increased ($P < 0.05$) when compared with the sham group. Compared with the OVX + NC group, the contents of DPD, OCN, OPN increased the OVX + ERK-5 shRNA group while declined in the OVX + ERK-5 overexpression group ($P < 0.05$) (Figure 5). Taken together, the above results demonstrated that ERK-5 contributed to reverse the abnormal bone turnover by regulating the functions of osteoblasts.

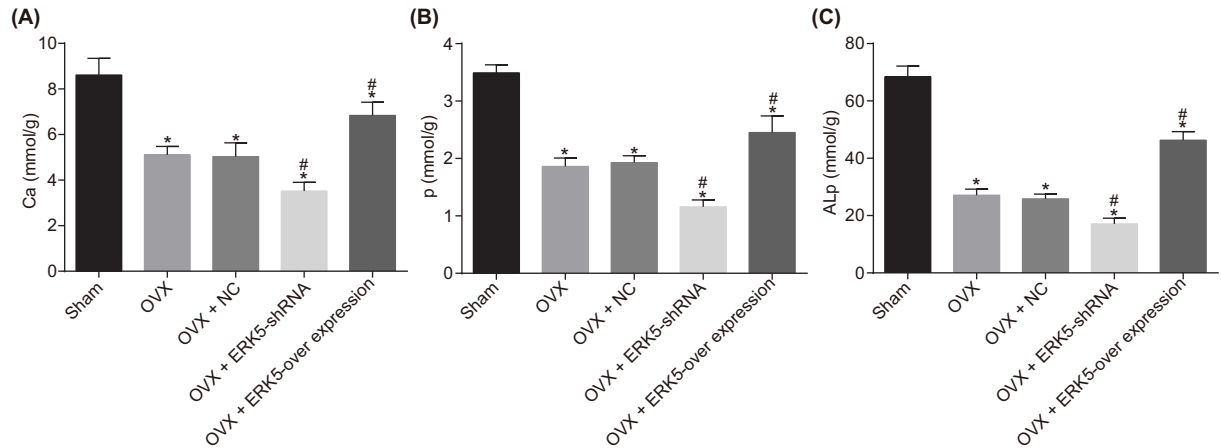


Figure 4. The contents of Ca, P and ALP were increased by ERK-5 overexpression

Bar graphs of the content of Ca (A), P (B) and ALP (C) measured by automatic biochemical analyzer in the sham-operated rats, ovariectomized rats without infection or ovariectomized rats infected with Lentivirus-GFP vector, Lentivirus-ERK-5-shRNA vector or Lentivirus-ERK-5-overexpression vector, respectively. $n=10$. * $P<0.05$ vs. the sham group; # $P<0.05$ vs. the OVX group. Abbreviations: OVX, ovariectomized rat; shRNA, short hairpin RNA.

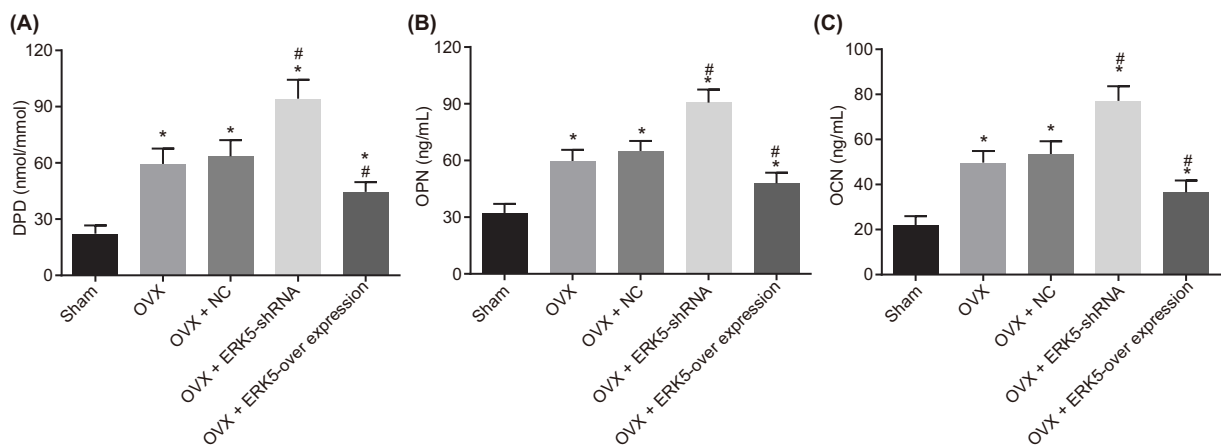


Figure 5. The contents of DPD, OPN and OCN were inhibited by up-regulation of ERK-5

DPD (A), OPN (B) and OCN (C) content variations in the the sham-operated rats, ovariectomized rats without infection or ovariectomized rats infected with Lentivirus-GFP vector, Lentivirus-ERK-5-shRNA vector or Lentivirus-ERK-5-overexpression vector, measured by ELISA. * $P<0.05$ vs. the sham group; # $P<0.05$ vs. the OVX group. Abbreviations: OVX, ovariectomized rat; shRNA, short hairpin RNA.

ERK-5 improves the viability of osteoblasts

The expression of ERK in osteoblasts was measured by Western blot assay in order to determine whether ERK siRNA and ERK overexpression vector were successfully transfected into the osteoblasts *in vitro*. The results obtained demonstrated that ERK expression was significantly decreased in ERK-5 siRNA group and increased in ERK-5 vector group compared with blank and NC groups (Figure 6A). The viability of osteoblasts was assessed through MTT assay. The results revealed that compared with the blank and NC group, the osteoblast viability declined obviously in the ERK-5 siRNA group while increased significantly in the ERK-5 vector group ($P<0.05$) (Figure 6B). The results provided evidence that ERK-5 could improve osteoblast viability.

ERK-5 inhibits osteoblast apoptosis

The cycle of osteoblasts was analyzed using flow cytometry. The results indicated that compared with the blank and NC groups, the osteoblast in G_1 phase increased significantly in the ERK-5 siRNA group while osteoblast in S phase

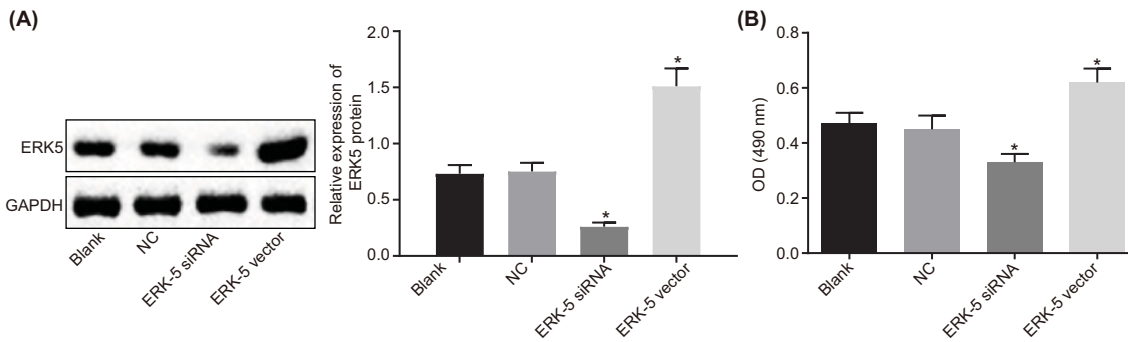


Figure 6. Cell proliferation is enhanced by ERK-5

(A) The expression of ERK normalized against GAPDH in osteoblasts without transfection or transfected with NC, ERK-5 siRNA or ERK-5 overexpression plasmid measured by Western blot assay. (B) The viability of osteoblast assessed by MTT assay. $n=10$. * $P<0.05$ vs. the blank and NC groups. The experiment was repeated three times.

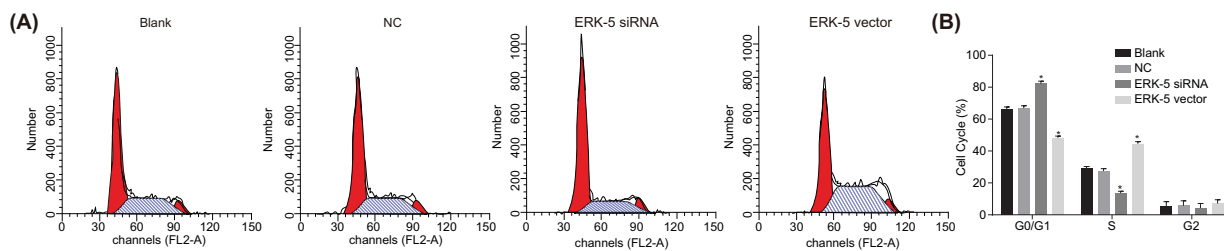


Figure 7. Cell cycle progression is promoted after enhancement of ERK-5

(A) Cell cycle distribution in osteoblasts without transfection or transfected with NC, ERK-5 siRNA or ERK-5 overexpression plasmid assessed by flow cytometry. (B) Quantitative analysis of proportions of cells in different phases. * $P<0.05$ vs. the blank and NC groups. The experiment was repeated three times. Abbreviation: siRNA, small interfering RNA.

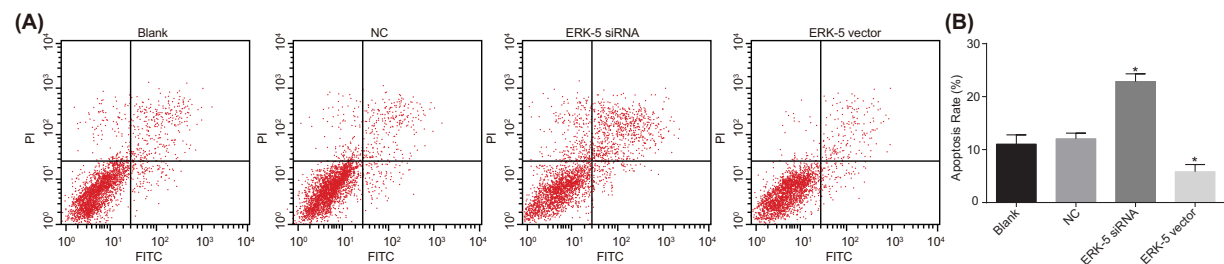


Figure 8. Cell apoptosis is inhibited by ERK-5

Flow chart of cell apoptosis (A) and apoptotic rate (B) in osteoblasts without transfection or transfected with NC, ERK-5 siRNA or ERK-5 overexpression vector. * $P<0.05$ vs. the blank and NC groups. The experiment was repeated three times. Abbreviation: siRNA, small interfering RNA.

was notably decreased ($P<0.05$); whereas, fewer osteoblasts were arrested in the G_1 phase with more osteoblasts in S phase in the ERK-5 vector group ($P<0.05$). The aforementioned results illustrated that ERK-5 could regulate osteoblast cycle through promoting osteoblast to enter S from G_1 phase (Figure 7).

The effects of ERK-5 on osteoblast apoptosis was measured using Annexin-V-FITC/PI double staining method. The results indicated that compared with the blank and NC groups, the apoptosis rate in the ERK-5 siRNA group increased greatly ($P<0.05$) and significantly declined in the ERK-5 vector group, verifying that ERK-5 could inhibit osteoblast apoptosis (Figure 8).

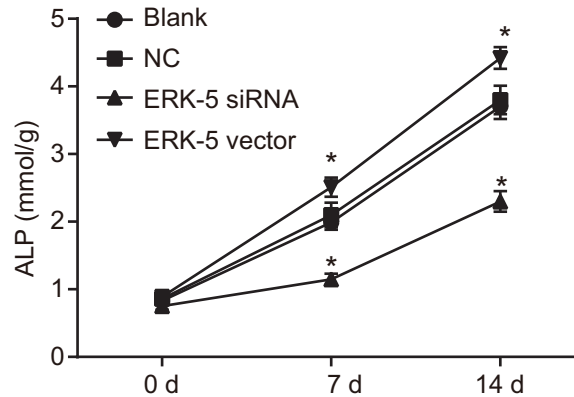


Figure 9. ALP activity is enhanced after transfection with ERK-5 overexpression vector

ALP activity in osteoblasts without transfection or transfected with NC, ERK-5 siRNA or ERK-5 overexpression plasmid was detected on the 7th and 14th days. * $P < 0.05$ vs. the blank and NC groups. The experiment was repeated three times. Abbreviation: siRNA, small interfering RNA.

ERK-5 improves the activity of ALP in osteoblast

The ALP activity of osteoblast was detected using ELISA. The ELISA results demonstrated that compared with the blank and NC groups, the ALP activity was decreased in the ERK-5 siRNA group at the 7th and 14th days after osteogenic induction ($P < 0.05$) while ascended obviously in the ERK-5 vector group ($P < 0.05$) (Figure 9). The results obtained proved that ERK-5 improved the activity of ALP in osteoblasts.

Discussion

Osteoporosis is mainly caused by exceeding bone resorption by osteoclasts during bone formation by osteoblasts [7,17]. Existing literature has provided evidence verifying the key role played by ERK-5 in promoting cell proliferation and differentiation [8]. The rats in our study were ovariectomized to stimulate postmenopausal osteoporosis to identify the role of ERK-5 in the proliferation and apoptosis of osteoblasts. Eventually, the study concluded that ERK-5 could improve the properties of femoral tissues, which ultimately inhibits the apoptosis and promotes proliferation of osteoblasts, thus improving postmenopausal osteoporosis.

Initially, the three-point bending test results showed that the ovariectomized rats exhibited a decrease in biomechanical properties. The postmenopausal women are more inclined to be affected by imbalanced bone metabolism because the estrogen which helps to maintain the bone mass through promoting osteoblast activity decreased and the decreased proliferation of osteoblasts results in bone loss [18]. Therefore, it is reasonable to speculate that an ovariectomy could lead to a reduction in the levels of estrogen, thus influencing the biomechanical properties of the rats caused by imbalanced bone metabolism. Bone turnover and BMD have been suggested to be two significant risk factors for fracture caused by osteoporosis which can be altered by pharmacology [19]. A previous study indicated that Romosozumab could increase the BMD of postmenopausal women with low bone mass [20], which leads to an increase in BMD and may help to ameliorate postmenopausal osteoporosis. In the present study, our findings suggested that BMD increased in the ERK-5 vector group, suggesting that ERK-5 could improve the BMD of rat's femurs which ultimately contributes to the alleviation of postmenopausal osteoporosis.

Subsequently, ovariectomized rats exhibited decreased content of bone metabolic markers Ca, P and ALP activity, and the content of bone turnover markers DPD, OCN and OPN increased in the osteoblasts. The unique process of bone formation comprises the mineralization phase which involves the attachment of Ca and phosphate as well as collagenous and other noncollagenous proteins [21]. ALP has been defined in literature as an endogenous enzyme which delivering detoxifying effects through dephosphorylation of endotoxins and pro-inflammatory extracellular ATP and is understood to be the most representative bone marker protein during the osteoblast differentiation process [21,22]. Supportively, a previous report demonstrated that integrins including $\alpha 5\beta 1$ and $\alpha v\beta 3$ play a role in the process of intracellular signaling cascade activation in addition to further promoting the expression of ALP and OCN in human bone mesenchymal cells (hBMSCs) osteogenic differentiation process, while integrins including $\alpha 1\beta 1$ and $\alpha 2\beta 1$ binding sites are reported to activate ERK [7]. In the present study, our results revealed that after Lentiviral-mediated ERK-5 overexpression in the ovariectomized rats, bone metabolism was improved and bone turnover was suppressed.

This finding clearly illustrated that ERK-5 overexpression could regulate the properties of femoral tissues, whereby ERK-5 confers its protective effect against postmenopausal osteoporosis.

The apoptosis of osteoblasts was inhibited by ERK-5 and osteoblast number in G₁ phase increased while decreased in S phase, and the viability of osteoblasts was increased. ERK-activating stimuli which contain mechanical stimulation, systemic hormones and local factors such as Wingless and INT-1, and Insulin-like growth factor gene - 1 could inhibit osteoblastic cell apoptosis [23]. ERK-5 has been shown to play a significant role in relation to various transcription factors including myocyte enhancer factor 2, p90 ribosomal S6 kinase, cAMP-regulated enhancer B and NF- κ B during phosphorylation process [24]. The ERK pathway, being highly induced in response to growth factors, cytokines and phorbol esters, has been shown to be strongly involved in the processes of cell growth and differentiation [25]. Furthermore, another study demonstrated that the elevated expression of osteogenic gene ALP, and promoted proliferative ability of the osteoblasts were achieved by activating the MAPK-ERK1/2 pathway [26]. A previous report indicated that ERK-5 could be regulated by mitogen/extracellular-signal-regulated kinase 5 (MEK5), which represents another important MAPK family member [27]. Additionally, Maria et al. [28] reported that MEK5 was involved in the osteoblast differentiation and osteogenic process. MEK-ERK-5 activation was required for the osteogenic differentiation and mineralization [29]. Therefore, we speculated that ERK-5 could inhibit the apoptosis of osteoblasts and promote differentiation by inhibiting the transcription process, synthetics of ERK-activating stimuli or growth factors.

In conclusion, our study indicates that the up-regulation of ERK-5 could lead to a reduction in bone turnover markers as well as an increase in bone metabolic markers. Elevation of ERK-5 could increase the BMD and proliferative ability of osteoblasts, and inhibit the apoptosis of osteoblasts in ovariectomized rats. Our results illustrate that ERK-5 may represent an effective therapeutic target for treatment of postmenopausal osteoporosis. However, our study only employed rat models but lacks clinical trials, thus multicenter case-control studies would be needed for the validation of the mechanisms underlying the role of ERK-5 in osteoporosis.

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Ethics Statement

The current study was performed in strict accordance with the guidelines for the care and use of laboratory animals of International Association for the Study of Pain. Animal experiments took place in Experimental Animal Center of Xianyang Central Hospital. The protocol was approved by the Laboratory Animal Ethics Committee of Xianyang Central Hospital. All painful procedures were performed under anesthesia, with extensive efforts made to minimize suffering [13].

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Competing Interests

The authors declare that there are no competing interests associated with the manuscript.

Author Contribution

T.-M.G. and G.-X.L. designed the study. Y.-L.X., L.Y. and X.-M.Q. collated the data, designed and developed the database, carried out data analyses and produced the initial draft of the manuscript. T.-M.G. and H.-Y.Z. contributed to drafting the manuscript. All authors have read and approved the final submitted manuscript.

Abbreviations

ALP, alkaline phosphatase; BMD, bone mineral density; Ca, calcium; DEXA, dual energy X-ray absorptiometry; DMEM, Dulbecco's modified Eagle's medium; DPD, deoxyypyridinoline; ELISA, enzyme-linked immunosorbent assay; ERK-5, extracellular signal-regulated kinase 5; FBS, fetal bovine serum; HE, Hematoxylin-Eosin; MAPK, mitogen-activated protein kinase; MEK5, mitogen/extracellular-signal-regulated kinase 5; MTT, 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide; NC, negative control; OCN, osteocalcin; OD, optical density; OPN, osteopontin; OVX, ovariectomized rat; P, phosphorus; PI, propidium iodide; SD, Sprague-Dawley; TBST, tris-buffered saline with tween.

References

- 1 Edwards, M.H., Dennison, E.M., Aihie Sayer, A., Fielding, R. and Cooper, C. (2015) Osteoporosis and sarcopenia in older age. *Bone* **80**, 126–130, <https://doi.org/10.1016/j.bone.2015.04.016>
- 2 Post, T.M., Cremers, S.C., Kerbusch, T. and Danhof, M. (2010) Bone physiology, disease and treatment: towards disease system analysis in osteoporosis. *Clin. Pharmacokinet.* **49**, 89–118, <https://doi.org/10.2165/11318150-000000000-00000>
- 3 Cosman, F., de Beur, S.J., LeBoff, M.S., Lewiecki, E.M., Tanner, B., Randall, S. et al. (2014) Clinician's guide to prevention and treatment of osteoporosis. *Osteoporos. Int.* **25**, 2359–2381, <https://doi.org/10.1007/s00198-014-2794-2>
- 4 Adler, R.A., El-Hajj Fuleihan, G., Bauer, D.C., Camacho, P.M., Clarke, B.L., Cines, G.A. et al. (2016) Managing osteoporosis in patients on long-term bisphosphonate treatment: report of a Task Force of the American Society for Bone and Mineral Research. *J. Bone Miner. Res.* **31**, 16–35, <https://doi.org/10.1002/jbmr.2708>
- 5 Andersen, C.Y. and Kristensen, S.G. (2015) Novel use of the ovarian follicular pool to postpone menopause and delay osteoporosis. *Reprod. Biomed. Online* **31**, 128–131, <https://doi.org/10.1016/j.rbmo.2015.05.002>
- 6 Golob, A.L. and Laya, M.B. (2015) Osteoporosis: screening, prevention, and management. *Med. Clin. North Am.* **99**, 587–606, <https://doi.org/10.1016/j.mcna.2015.01.010>
- 7 Hu, H.M., Yang, L., Wang, Z., Liu, Y.W., Fan, J.Z., Fan, J. et al. (2013) Overexpression of integrin $\alpha 2$ promotes osteogenic differentiation of hBMSCs from senile osteoporosis through the ERK pathway. *Int. J. Clin. Exp. Pathol.* **6**, 841–852
- 8 Dwivedi, Y., Rizavi, H.S., Teppen, T., Sasaki, N., Chen, H., Zhang, H. et al. (2007) Aberrant extracellular signal-regulated kinase (ERK) 5 signaling in hippocampus of suicide subjects. *Neuropsychopharmacology* **32**, 2338–2350, <https://doi.org/10.1038/sj.npp.1301372>
- 9 Abdelmohsen, K., Sauerbier, E., Ale-Agha, N., Beier, J., Walter, P., Galban, S. et al. (2007) Epidermal growth factor- and stress-induced loss of gap junctional communication is mediated by ERK-1/ERK-2 but not ERK-5 in rat liver epithelial cells. *Biochem. Biophys. Res. Commun.* **364**, 313–317, <https://doi.org/10.1016/j.bbrc.2007.09.132>
- 10 Lennartsson, J., Burovic, F., Wittek, B., Jurek, A. and Heldin, C.H. (2010) Erk 5 is necessary for sustained PDGF-induced Akt phosphorylation and inhibition of apoptosis. *Cell. Signal.* **22**, 955–960, <https://doi.org/10.1016/j.cellsig.2010.01.020>
- 11 Xing, L.Z., Ni, H.J. and Wang, Y.L. (2017) Quercitrin attenuates osteoporosis in ovariectomized rats by regulating mitogen-activated protein kinase (MAPK) signaling pathways. *Biomed. Pharmacother.* **89**, 1136–1141, <https://doi.org/10.1016/j.biopha.2017.02.073>
- 12 Lee, W.C., Guntur, A.R., Long, F. and Rosen, C.J. (2017) Energy metabolism of the osteoblast: implications for osteoporosis. *Endocr. Rev.* **38**, 255–266, <https://doi.org/10.1210/er.2017-00064>
- 13 Orlans, F.B. (1997) Ethical decision making about animal experiments. *Ethics Behav.* **7**, 163–171, <https://doi.org/10.1207/s15327019eb07027>
- 14 Chandler, H., Brooks, D.J., Hattersley, G., Bouxsein, M.L. and Lanske, B. (2019) Abaloparatide increases bone mineral density and bone strength in ovariectomized rabbits with glucocorticoid-induced osteopenia. *Osteoporos. Int.*, <https://doi.org/10.1007/s00198-019-04999-4>
- 15 Shiraishi, A., Takeda, S., Masaki, T., Higuchi, Y., Uchiyama, Y., Kubodera, N. et al. (2000) Alfacalcidol inhibits bone resorption and stimulates formation in an ovariectomized rat model of osteoporosis: distinct actions from estrogen. *J. Bone Miner. Res.* **15**, 770–779, <https://doi.org/10.1359/jbmr.2000.15.4.770>
- 16 Dong, X.L., Li, C.M., Cao, S.S., Zhou, L.P. and Wong, M.S. (2016) A high-saturated-fat, high-sucrose diet aggravates bone loss in ovariectomized female rats. *J. Nutr.* **146**, 1172–1179, <https://doi.org/10.3945/jn.115.225474>
- 17 Tong, X., Gu, P.C., Xu, S.Z. and Lin, X.J. (2015) Long non-coding RNA-DANCR in human circulating monocytes: a potential biomarker associated with postmenopausal osteoporosis. *Biosci. Biotechnol. Biochem.* **79**, 732–737, <https://doi.org/10.1080/09168451.2014.998617>
- 18 Wei, J., Wang, J., Gong, Y. and Zeng, R. (2015) Effectiveness of combined salmon calcitonin and aspirin therapy for osteoporosis in ovariectomized rats. *Mol. Med. Rep.* **12**, 1717–1726, <https://doi.org/10.3892/mmr.2015.3637>
- 19 Papapoulos, S., Lippuner, K., Roux, C., Lin, C.J., Kendler, D.L., Lewiecki, E.M. et al. (2015) The effect of 8 or 5 years of denosumab treatment in postmenopausal women with osteoporosis: results from the FREEDOM Extension study. *Osteoporos. Int.* **26**, 2773–2783, <https://doi.org/10.1007/s00198-015-3234-7>
- 20 McClung, M.R., Grauer, A., Boonen, S., Bolognese, M.A., Brown, J.P., Diez-Perez, A. et al. (2014) Romosozumab in postmenopausal women with low bone mineral density. *N. Engl. J. Med.* **370**, 412–420, <https://doi.org/10.1056/NEJMoa1305224>
- 21 Seo, H.J., Cho, Y.E., Kim, T., Shin, H.I. and Kwun, I.S. (2010) Zinc may increase bone formation through stimulating cell proliferation, alkaline phosphatase activity and collagen synthesis in osteoblastic MC3T3-E1 cells. *Nutr. Res. Pract.* **4**, 356–361, <https://doi.org/10.4162/nrp.2010.4.5.356>
- 22 Pickkers, P., Heemskerk, S., Schouten, J., Laterre, P.F., Vincent, J.L., Beishuizen, A. et al. (2012) Alkaline phosphatase for treatment of sepsis-induced acute kidney injury: a prospective randomized double-blind placebo-controlled trial. *Crit. Care* **16**, R14, <https://doi.org/10.1186/cc11159>
- 23 Bivi, N., Condon, K.W., Allen, M.R., Farlow, N., Passeri, G., Brun, L.R. et al. (2012) Cell autonomous requirement of connexin 43 for osteocyte survival: consequences for endocortical resorption and periosteal bone formation. *J. Bone Miner. Res.* **27**, 374–389, <https://doi.org/10.1002/jbmr.548>
- 24 Elkins, J.M., Wang, J., Deng, X., Pattison, M.J., Arthur, J.S., Erazo, T. et al. (2013) X-ray crystal structure of ERK5 (MAPK7) in complex with a specific inhibitor. *J. Med. Chem.* **56**, 4413–4421, <https://doi.org/10.1021/jm4000837>
- 25 Wang, X., Martindale, J.L. and Holbrook, N.J. (2000) Requirement for ERK activation in cisplatin-induced apoptosis. *J. Biol. Chem.* **275**, 39435–39443, <https://doi.org/10.1074/jbc.M004583200>
- 26 Ding, D., Li, L., Song, Y., Du, G., Wei, X. and Cao, Y. (2013) MAPK-ERK1/2 signaling pathway regulates osteogenic gene expression in rat osteoblasts *in vitro*. *Nan. Fang Yi Ke Da Xue Xue Bao* **33**, 1432–1436
- 27 Nithianandarajah-Jones, G.N., Wilm, B., Goldring, C.E., Muller, J. and Cross, M.J. (2012) Erk5: structure, regulation and function. *Cell. Signal.* **24**, 2187–2196, <https://doi.org/10.1016/j.cellsig.2012.07.007>

- 28 Maria, S., Samsonraj, R.M., Munmun, F. et al. (2018) Biological effects of melatonin on osteoblast/osteoclast cocultures, bone, and quality of life: Implications of a role for mt2 melatonin receptors, mek1/2, and mek5 in melatonin-mediated osteoblastogenesis. *J. Pineal Res.* **64**, <https://doi.org/10.1111/jpi.12465>
- 29 Zhao, L.G., Chen, S.L., Teng, Y.J. et al. (2014) The mek5/erk5 pathway mediates fluid shear stress promoted osteoblast differentiation. *Connect. Tissue Res.* **55**, 96–102, <https://doi.org/10.3109/03008207.2013.853755>