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Wang, N., Robaye, B., Agrawal, A. et al. (3 more authors) (2011) Reduced Bone Turnover in Mice Lacking the P2Y13 Receptor of ADP. Molecular Endocrinology, 26 (1). pp. 142-152. ISSN 0888-8809

https://doi.org/10.1210/me.2011-1083

Title: Reduced bone turnover in mice lacking the $P2Y_{13}$ receptor of ADP.

Short Title: Reduced bone turnover in $P2Y_{13}$ KO mice

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Key words: $P2Y_{13}$ receptor, knock-out, osteoblasts, osteoclasts, OVX

Funding Source: European Commission under the 7th Framework Programme (proposal #202231) performed as a collaborative project among the members of the ATPBone Consortium (Copenhagen University, University College London, University of Maastricht, University of Ferrara, University of Liverpool, University of Sheffield, and Université Libre de Bruxelles), and is a sub study under the main study "Fighting osteoporosis by blocking nucleotides: purinergic signalling in bone formation and homeostasis"

Disclosure summary:

All authors have nothing to disclose.

Abstract:

Osteoporosis is a condition of excessive and un-coupled bone turnover in which osteoclastic resorption exceeds osteoblastic bone formation, resulting in an overall net bone loss, bone fragility and morbidity. While numerous treatments have been developed to inhibit bone loss by blocking osteoclastic bone resorption, understanding of the mechanisms behind bone loss is incomplete. The purinergic signalling system is emerging to be a pivotal regulator of bone homeostasis and extracellular ADP has previously been shown to be a powerful osteolytic agent in vitro. We report here that deletion of the $P2Y_{13}$ receptor, a G-protein coupled receptor for extracellular ADP, leads to a 40% reduction in trabecular bone mass, 50% reduction in osteoblast and osteoclast numbers in vivo as well as activity in vitro and an overall 50% reduction in the rate of bone remodelling in mice in vivo. Down-regulation of RhoA/ROCK I signalling and a reduced ratio of RANKL/OPG observed in osteoblasts from $P2Y_{13}R^{-/-}$ mice might explain this bone phenotype. Furthermore, as one of the main causes of osteoporosis in older women is lack of estrogen, we examined the effect of ovariectomy (OVX) of the $P2Y_{13}R^{-/-}$ mice and found them to be protected from OVX-induced bone loss by up to 65%. These data confirm a role of purinergic ADP signalling in the skeleton, whereby deletion of the receptor leads to reduced bone turnover rates which provide a protective advantage in conditions of accelerated bone turnover such as oestrogen deficiency-induced osteoporosis.

Key words: $P2Y_{13}$ receptor, knock-out, osteoblasts, osteoclasts, OVX

Introduction

The membrane-bound receptors for extracellular nucleotides known as P2 receptors can be divided into two major families based on their signal transduction mechanisms and topology. P2X receptors form a family of ligand-gated ion channels with signal transduction cascade via non-selective outward cation currents, whilst P2Y receptors form a family of G protein-coupled receptors coupled to G_q or/and G_i (1). Both osteoblasts and osteoclasts express numerous P2 receptor subtypes in a spatial and temporal manner (2). Specifically in osteoblasts, ATP and its degradation product adenine diphosphate (ADP) have been shown to modulate $[Ca^{2+}]_i$ calcium signalling (3), increase cell proliferation (4), increase expression of Receptor Activator of NF-κb Ligand (RANKL) (a key modulator of osteoclast formation and resorption) (5) and intriguingly, synergise with PTH to induce activation of c-fos, a key transcription factor in bone (6). This last observation suggests that ATP and P2 receptors represent a local mechanism enabling the bone remodelling induced by systemic hormones such as PTH to be confined to discrete foci. In osteoclasts, ATP appears to have both stimulatory (7, 8) and inhibitory roles via P2 receptors (9, 10), whilst ADP was shown to be a powerful osteolytic agent reportedly acting via the $P2Y_1$ receptor (11). In vivo knockout models have offered further insights into the overall effect on bone homeostasis of the different, but highly significant effects of extracellular nucleotides. $P2Y_2$ receptor deficient mice demonstrate a striking increase in bone mineral content, presumably related to the inhibitory effect of ATP on mineralization by osteoblasts (12). On the contrary, the $P2X_7$ receptor deficient mice do not have an extreme skeletal phenotype (13) but exhibit site-specific alterations in bone formation and resorption (14). A recent preliminary investigation of $P2Y_1$ receptor deficient mice revealed a reduced bone mass, confirming a role for ADP in bone homeostasis (15).

In addition to the $P2Y_1$ and $P2Y_{12}$ receptor, the $P2Y_{13}$ receptor, originally named GPR86 (16), has high affinity for ADP (17). The $P2Y_{13}$ receptor is a G_i-coupled receptor which shows a high level of identity with $P2Y_{12}$ and $P2Y_{14}$ receptors, sharing 45-48% amino acid sequence identity (17). Similarly to the $P2Y_1$ and $P2Y_{12}$ receptors, $P2Y_{13}$ receptors respond to ADP in the nanomolar range (18). Expression of $P2Y_{13}$ receptor mRNA has been shown in abundance in the brain, spleen, lymph nodes

and bone marrow, suggesting roles in nervous, haematopoietic, and immune systems. A lower level of expression is found in liver, lung, placenta, and spinal cord (17-19). Although $P2Y_{13}$ receptors are detected in different tissues, the physiological function of this receptor is still unclear. Several reports suggesting a role of $P2Y_{13}$ receptors are not entirely convincing due to the lack of truly selective agonists and antagonists for this receptor (20-25). Indeed Cangrelor (AR-C69931MX) behaves as a $P2Y_{13}$ receptor antagonist (26) or partial agonist (27), although it was primarily described as a specific $P2Y_{12}$ receptor antagonist and is currently in clinical development as an antithrombotic agent. The study of $P2Y_{13}$ receptor-deficient mice ($P2Y_{13}R^{-/-}$) has so far revealed the role of this receptor in HDL cholesterol uptake by hepatocytes and reverse cholesterol transport (28, 29). In the context of bone, the expression of $P2Y_{13}$ receptors in osteoblasts and osteoclasts has been recently confirmed (30, 31). Taken together with the previous reports of the powerful effect of ADP on osteoclasts, we sought to determine the consequence of $P2Y_{13}$ receptor gene deletion on the bones of mice. Using micro computer tomography (μCT) we show that the bones of the $P2Y_{13}R^{-/-}$ mice have altered bone mass, due to reduced numbers of osteoblasts and osteoclasts in the bone as shown by histology. Dynamic histomorphometry confirmed reduced mineral apposition and bone formation rates, whilst in vitro primary cell cultures were used to determine the effect of gene deletion on the formation and function of osteoblasts and osteoclasts. Finally, ovariectomy (OVX), a widely accepted model of bone changes after menopause (32), revealed that $P2Y_{13}R^{-/-}$ mice were protected from OVX-induced bone loss by up to 65%. These findings confirm a role for the $P2Y_{13}$ receptor in bone remodelling, offering a potential novel therapeutic target for fighting bone diseases in conditions of accelerated bone turnover such as oestrogen deficiency-induced osteoporosis.

Results

Reduced trabecular bone volume in $P2Y_{13}R^{-/-}$ mice

There was no severe or obvious gross morphological difference between the whole skeleton of $P2Y_{13}R^{-/-}$ and wild type (WT) mice upon macroscopic examination or using μCT 3D models of the whole tibia (Fig. 1A). However, μCT analysis revealed that although the length of the tibia was not significantly different, $P2Y_{13}R^{-/-}$ mice had ~5% less total bone volume in the tibia compared with WT

(Fig. 1C, $p < 0.05$). Analysis of the microstructure of the bone in the tibia at a higher resolution revealed 37.5% less trabecular bone ($p < 0.001$)(Fig. 1D) and 37.8% fewer trabeculae in $P2Y_{13}R^{-/-}$ mice compared to WT ($p < 0.001$) (Fig. 1E). Other typical trabecular bone parameters are summarised in Table 1. μCT analysis on a predominantly cortical bone region showed no significant effects on cortical bone parameters including cortical bone volume ($p = 0.09$), endosteal diameter ($p = 0.41$) and periosteal diameter ($p = 0.48$) (Table 1).

Reduced osteoclast and osteoblast numbers in long bones of $P2Y_{13}R^{-/-}$ mice

Assessment of the cellular compartment of the bone by histological analysis showed that there were approximately half as many osteoclasts ($p < 0.05$) and osteoblasts ($p < 0.05$) on the surfaces of the cortical bone in $P2Y_{13}R^{-/-}$ mice compared with WT controls (Fig. 2A-2D). In the trabecular region of the tibia, $P2Y_{13}R^{-/-}$ mice had 22% fewer osteoblasts per mm trabecular surface compared with WT controls ($p < 0.05$) (Fig. 2E-2G) though no significant reduction in osteoclast numbers.

$P2Y_{13}R^{-/-}$ mice have reduced rates of bone formation in vivo

To determine whether deletion of the $P2Y_{13}$ receptor would lead to reduced remodelling, 16 week-old mice were given intraperitoneal injections of calcein (30 mg/kg) 14 days and 2 days prior to being euthanized to allow for assessment of the rate and extent of mineralization (Fig. 3A). Comparing the $P2Y_{13}R^{-/-}$ with WT mice, the mineral apposition rate and bone formation rate were both significantly reduced by nearly 50% in the tibia ($p < 0.0001$ and $p < 0.0001$) (Fig. 3B+C).

Loss of $P2Y_{13}R$ leads to reduced osteoblast function in vitro

To determine whether osteoblast function is altered in $P2Y_{13}R^{-/-}$ mice, primary osteoblasts were isolated and cultured in vitro. There were no significant differences in the proliferation rates of $P2Y_{13}R^{-/-}$ osteoblasts compared with WT mice over a 5-day period (Fig. 4A). However, a 50% reduction in mineralization was observed in long term differentiation cultures compared to WT ($p < 0.0001$)(Fig. 4B+C). These data confirm that $P2Y_{13}R$ is involved in normal osteoblast function.

Loss of $P2Y_{13}R$ leads to reduced osteoclast formation in vitro

TRAP positive osteoclasts with three or more nuclei were identified when isolated monocytes from both WT and $P2Y_{13}R^{-/-}$ mice were cultured on glass coverslips in the presence of M-CSF and RANKL for 10 days (Fig. 4D, black arrows). The number of multinucleated osteoclasts formed from $P2Y_{13}R^{-/-}$ mice was 50% lower when compared with WT ($p < 0.0001$) (Fig. 4E). To determine the effect on osteoclast function, isolated monocytes were cultured in the presence of M-CSF and RANKL for 17 days on dentine disks and the number of resorbing osteoclasts (Fig 4F, black arrows) and amount of resorption were quantified (Fig 4F, white arrows). There were 47.1% fewer resorbing osteoclasts from $P2Y_{13}R^{-/-}$ mice ($p = 0.0004$) (Fig 4G) which resulted in 66% less total resorption ($p < 0.0001$) (Fig. 4H). However, there was no significant difference in the amount of resorption per functional, resorbing osteoclast ($p = 0.5$) (Fig. 4I).

Down-regulation of key regulatory genes in $P2Y_{13}R^{-/-}$ mice

To delineate the effect of P2ry13 gene deletion on downstream signalling pathways, a TaqMan custom array was used to analyse cDNA from primary osteoblasts and long bone marrow of both $P2Y_{13}R^{-/-}$ and WT mice. Results confirmed the absence of the $P2Y_{13}$ receptor mRNA in osteoblasts and bone marrow from $P2Y_{13}R^{-/-}$ mice, further confirming successful deletion of the gene. The difference in expression for each target cDNA between the WT and $P2Y_{13}R^{-/-}$ mice was analyzed using the CT relative quantification method (33). In primary osteoblasts, compared to WT the expression of RhoA was significantly down-regulated (0.10 fold change) and Tnfrsf11b (the gene for OPG) was up-regulated (2.25 fold change) in $P2Y_{13}R^{-/-}$ mice (Fig. 4J). In bone marrow samples Mapk3 (0.02 fold change), Rock1 (0.25 fold change), RhoA (0.12 fold change), and Tnfsf11 (RANKL, 0.45 fold change) were all significantly down-regulated (Fig. 4K).

Estrogen deficiency-induced bone loss is attenuated in $P2Y_{13}R^{-/-}$ mice

Accelerated bone loss after the menopause is a primary cause of osteoporosis in women. To determine if the reduced osteoclast function seen in $P2Y_{13}R^{-/-}$ mice may attenuate estrogen deficiency-induced bone loss, OVX surgery was performed on 4 month old mice. Four weeks after surgery, there was a

significant difference in the response of $P2Y_{13}R^{-/-}$ mice compared to WT mice in BMD ($p < 0.05$) and trabecular thickness ($p < 0.001$). A significant loss of BMD in WT mice ($p < 0.001$) was observed at 4 weeks compared to baseline, but not in $P2Y_{13}R^{-/-}$ mice (Fig. 5A). μCT analysis of the trabecular bone structure of the tibial region demonstrated significant thinning of the individual trabeculae in WT mice at 4 weeks compared to baseline ($p < 0.0001$) but not in $P2Y_{13}R^{-/-}$ mice (Fig. 5B). Interestingly, 12 weeks after surgery the protection from OVX-induce bone loss in $P2Y_{13}R^{-/-}$ mice was more apparent ($p < 0.001$ for both parameters compared with WT). In WT mice, BMD and trabecular thickness were still reduced compared with baseline (Fig. 5A, $p < 0.05$ and Fig. 5B $p < 0.0001$ respectively) whereas the $P2Y_{13}R^{-/-}$ mice showed an increase in both BMD ($p < 0.05$) and trabecular thickness compared with baseline levels (Fig. 5A and B respectively).

Discussion

The $P2Y_{13}$ receptor is widely distributed in different tissues and cell types, including osteoclasts and osteoblasts (30, 31). Given the emerging important role of the purinergic signalling pathway in the bone microenvironment and bone remodelling, we wanted to investigate the consequence of $P2Y_{13}$ receptor deletion on the skeleton. Deletion of $P2Y_{13}$ receptor had no effect on the gross physiology of the mice, which were healthy and fertile. When examining the bone using μCT analysis, we found that the $P2Y_{13}R^{-/-}$ mice had less bone volume in the whole tibia although the overall length was unchanged. A more detailed analysis using high resolution μCT scan was performed to determine which bone compartment was the source of the observed reduction in bone. Data obtained from the proximal tibia revealed that the $P2Y_{13}R^{-/-}$ mice had almost 40% less trabecular bone and trabecular number. The $P2Y_{13}R^{-/-}$ mice also had significantly higher trabecular pattern factor and structural model index, which indicates a less well-connected and more rod-like structured trabecular bone, in contrast to the well connected and flat structure typically seen in normal healthy animals (34, 35). There were no significant changes in any of the relevant indices for cortical bone.

To investigate further the observed bone phenotype, histomorphometric analysis demonstrated that the $P2Y_{13}R^{-/-}$ mice have half the number of osteoclasts and osteoblasts per unit of bone on the endocortical bone surface, whilst in the trabecular bone only a reduction in osteoblast numbers was observed. This imbalance in osteoblast to osteoclast numbers on the trabecular bone surface may explain the loss of trabecular bone in this region, whilst the equal reduction of both osteoblasts and osteoclasts on the cortical surface would lead to no net loss of bone. In vitro primary bone marrow cell cultures confirmed that deletion of the $P2Y_{13}$ receptor significantly reduced the capacity of bone marrow cells to form multinuclear, functional osteoclasts. This led to the significant decrease in total resorption observed, whereas the amount of resorption per osteoclast was not different from that of osteoclasts derived from WT bone marrow. Interestingly, primary osteoblast cultures demonstrated that the cells from $P2Y_{13}R^{-/-}$ mice had reduced function, leading to a 50% decrease in mineralization. These in vitro results are consistent with the 50% decrease in bone apposition rate and bone formation rate detected in $P2Y_{13}R^{-/-}$ mice using dynamic histomorphometry. Coupled with the reduction in the

number of osteoclasts this would result in an overall reduced bone remodelling rate, especially the bone formation rate, in 4 month old $P2Y_{13}R^{-/-}$ mice. Due to the relatively higher turnover activity in trabecular bone than in cortical bone (36), fewer functional osteoblasts and a lower bone formation rate will have affected trabecular bone to a greater extent than cortical bone.

Data obtained from the TaqMan custom array analysis provide possible explanations at the molecular level for the observed effect of $P2Y_{13}$ receptor deletion on osteoblasts and osteoclasts. The down-regulation of the expression of RhoA was found in both primary $P2Y_{13}R^{-/-}$ osteoblasts and bone marrow. There is evidence that the $P2Y_{13}R$ is upstream of the RhoA/ROCK I signalling controlling HDL endocytosis in human hepatocytes (37). Our data indicate that in addition to this acute activation of the RhoA pathway, the $P2Y_{13}$ receptor would also control the level of RhoA and ROCK1. Inhibition of RhoA/ROCK I signalling will reduce extracellular signal-regulated kinase (ERK) activity, diminish RUNX2 activity, and alter ALP activity in osteoblasts (38). Down regulation of ERK signalling via RhoA/ROCK I signalling in osteoclasts has previously been shown to impair survival and induce apoptosis in osteoclasts by affecting the formation of a ruffled border and the maintenance of cell polarity (39, 40). Interestingly, mRNA of Mapk3 was decreased in $P2Y_{13}R^{-/-}$ bone marrow. Therefore, the deletion of $P2Y_{13}R$ may lead to the down regulation of RhoA/ROCK I signalling, which in turn affects the downstream ERK-MAPK signalling causing reduced function and differentiation of bone cells, particularly osteoblasts. The other interesting finding with the TaqMan analysis was the up-regulation of Tnfrsf11b (osteoprotegerin, OPG) in the $P2Y_{13}R^{-/-}$ osteoblasts and the down-regulation of Tnfsf11 (RANKL) in $P2Y_{13}R^{-/-}$ mice bone marrow. These gene expression alterations would indicate an overall reduced ratio of RANKL/OPG and hence negative regulation of osteoclastogenesis, which may explain the phenomenon of reduced osteoclast formation observed in $P2Y_{13}R^{-/-}$ mice both in vivo and in vitro.

Osteoporosis is a condition in which there is over-activated bone turnover and in which osteoclast resorption exceeds osteoblastic bone formation leading to an overall net bone loss and bone fragility (41, 42). Bone loss accelerates in older women due to the menopause because estrogen withdrawal

increases the rate of bone remodelling - coupled with negative bone balance this produces bone loss and trabecular thinning (43). To investigate the pharmaceutical potential of lower bone turnover activities induced by the deletion of $P2Y_{13}R$, both $P2Y_{13}R^{-/-}$ and WT mice were ovariectomized to examine the bone changes under estrogen deficiency-induced osteoporosis. Four weeks after the OVX surgery, $P2Y_{13}R^{-/-}$ mice showed no significant loss of BMD, and even showed increased BMD 12-weeks after surgery. The observation that the $P2Y_{13}R^{-/-}$ mice have an attenuated response to estrogen deficiency-induced bone loss highlights this receptor as a possible new therapeutic target for osteoporosis. This is timely given the growing concern over the possible association of atypical fractures of the femur with long-term use of bisphosphonates (44). Bisphosphonates work by inhibiting the catabolic actions of osteoclasts leading to an overall suppression of bone turnover. Long term suppression of bone turnover may lead to the accumulation of microdamage in bone because of a failure to efficiently remove cracks which will ultimately lead to fracture of the bone (45). Targeting the $P2Y_{13}R$ may provide an alternative treatment which slows down the accelerated bone loss observed in post-menopausal women whilst maintaining turnover activities at a reduced rate to ensure repair of microdamage.

In conclusion, this is the first detailed study to examine the role of $P2Y_{13}$ receptor in bone homeostasis both in vivo and in vitro. Deletion of the $P2Y_{13}$ receptor leads to less trabecular bone in mice, by affecting both osteoblasts and osteoclasts. As a consequence, a lower bone apposition rate and bone formation rate were detected in 4 month old $P2Y_{13}R^{-/-}$ female mice. The down-regulation of RhoA/ROCK I signalling and a reduced ratio of RANKL/OPG may be the possible molecular mechanisms causing these bone phenotype alterations. The lower bone remodelling activity and the apparent protection from OVX-induced bone loss in $P2Y_{13}R^{-/-}$ mice suggest a possible new target for fighting bone diseases such as osteoporosis in the future.

MATERIALS AND METHODS

Mice

The strain of $P2Y_{13}$ receptor knockout ($P2Y_{13}R^{-/-}$) mouse was generated by classical homologous recombination in ES cells and aggregation with morulae as previously described (46). Briefly, the targeting of the P2ry13 gene was obtained by replacing a 1200 bp fragment containing the first non coding exon and the first 182 bp from the ATG starting coding sequence by a neomycin-resistance cassette. Male chimeras obtained from two different ES cells colonies were used to generate the $P2Y_{13}R^{-/-}$ mouse strain. Targeting of the gene was confirmed by Southern blotting and RT-PCR. The $P2Y_{13}$ mutation was crossed on C57BL/6J background for 10 generations. $P2Y_{13}R^{-/-}$ and wild type (WT) mice were housed in the same environmentally controlled conditions with a 12hr light/dark cycle at 22°C. They were free to access 2018 Teklad Global 18% Protein Rodent Diet containing 1.01% Calcium (Harlan Laboratories, UK) and water ad libitum in sterile RB-3 cages. For bone phenotype investigations, female mice were euthanized at 16 week of age. For dynamic histomorphometry, mice were given intraperitoneal injections of calcein (30 mg/kg) 14 days and 2 days prior to being euthanized. Hind limbs were dissected free of attached soft tissue for bone phenotype investigation. The lengths of tibiae were measured from the lowest point of the distal end to the highest point of the proximal end using calibrated vernier callipers. All procedures complied with the UK Animals (Scientific Procedures) Act 1986 and were reviewed and approved by the local Research Ethics Committee of the University of Sheffield (Sheffield, UK).

μCT

Right tibiae were dissected, fixed in 70% ethanol and scanned by SkyScan 1172 desktop μCT (SkyScan) at the resolution of 4.3μm for the tibia proximal end and 17.3μm for the whole tibia. The X-ray source was operated at 50kV and 200μA with a 0.5 aluminium filter. Two-dimensional CT images were captured every 0.7^{o} through 180^{o} rotation of the bone and were then reconstructed by Skyscan NRecon software at threshold of 0.0-0.16 and 0.0-0.14 for tibia proximal end and whole tibia scan respectively. Region of interest (ROI) was selected and analyzed by Skyscan CTan software. For

the proximal tibia scan, trabecular morphometry was characterized by measuring structural parameters from a 1.0mm thick trabecular abundant region which is 0.2mm below the growth plate. The parameters included the Bone Mineral density (BMD), bone volume fraction (BV/TV), trabecular thickness (Tb.Th), and trabecular number (Tb.N). Cortical bone parameters, including cortical bone volume (Ct.BV), endosteal diameter (Es. Dm), and periosteal diameter (Ps. Dm), were quantified from a 1.0mm thick predominantly cortical region 1.0mm below the growth plate.

Bone histomorphometry

The left tibiae were fixed in 10% buffered formalin, decalcified in 14.3% EDTA for 28 days, and then embedded in paraffin wax. Sections were cut (at 3µm) using a Leica Microsystems Microtome and TRAP stained as described previously (47, 48). Briefly, sections were incubated in prewarmed Acetate-tartrate buffer (0.1M Sodium tartrate (Sigma) in 0.2M Acetate buffer (Sigma), pH5.2) at 37°C for 5 mins, followed by 30 mins incubation at 37°C in 20mg/mL Naphthol AS-BI phosphate (Sigma) /Dimethylformamide (Fisher) in Acetate-tartrate buffer. The sections were then incubated in Acetate-tartrate buffer hexazotised pararosaniline solution, rinsed in water and counterstained in Gill's haematoxylin. The number of osteoblasts (N.Ob/B.Pm) and the number of osteoclasts were determined on a 3mm length of endocortical surface and a 0.75 mm^2 trabecular bone area, starting 0.25mm from the growth plate and viewed on a DMRB microscope (Leica Microsystems)(47). For dynamic histomorphometry, right tibiae were dissected and fixed in 70% ethanol, followed by embedded into LR White resin (Taab Laboratory Equipment Ltd). Sections were cut at 10µm using a Leica Microsystems Microtome. Mineral apposition rate (MAR) and the bone formation rate (BFR/BS) were obtained using a DMRB microscope as described previously (47). All histomorphometric parameters were based on the report of the ASBMR Histomorphometry nomenclature (49) and were obtained using the Osteomeasure bone histomorphometry software (Osteometrics)

Primary osteoblast isolation

Neonatal mouse calvariae (less than 72 hours old, 5-7 pups per culture) were dissected and the attached soft tissue was removed by digestion in 1mg/ml Collagenase 1A (Sigma) for 15 mins. Calvariae were then subjected to serial digestion in 1mg/mL Collagenase 1A for 30 mins; 0.25% Trypsin/EDTA (Gibco) for 30 mins; and 1mg/mL Collagenase 1A for 30 mins, at 37°C. All cells were harvested from the digestion suspensions and seeded into a T75 flask and cultured until confluent in DMEM© GLUTAMAX™ medium with sodium pyruvate (Gibco), 100 Units/mL Penicillin and 100 µg/mL Streptomycin (Gibco) and 10% foetal calf serum (FCS) (Gibco).

Proliferation Assay

First passage primary osteoblast cells isolated from $P2Y_{13}R^{-/-}$ and WT neonatal calvaria were seeded at a density of 5 $x10^3$ cells per well of a 96-well plate and cultured in DMEM© GLUTAMAX™ medium with sodium pyruvate, 100 Units/mL Penicillin and 100 µg/mL Streptomycin and 10% FCS for 5 days. On day 5, samples were examined by 3-(4,5-dimethylthiazol-2-yl) -5- (3-carboxymethoxyphenyl) -2- (4-sulfophenyl)-2H-tetrazolium, inner salt (MTS) assay (Promega) according to the manufacturer's instructions. The absorbance was read at 490nm on a SpectraMax $M5^e$ Microplate Reader (Molecular Devices).

Mineralization assay

First passage primary osteoblast cells were initially seeded at 1.5 x 10^4 cell/well in 12-well plate and cultured in growth medium for six days and changed into differentiation medium: DMEM© GLUTAMAX™ with sodium pyruvate, 100 Units/mL Penicillin and 100 µg/mL Streptomycin, 10% Fetal calf serum, 10nM Dexamethasone (Sigma), 50µg/mL L-Ascorbate Acid (Sigma), and 2mM β-glycerophosphate (Sigma)(50, 51). Cells were cultured in differentiation medium for three weeks and medium was changed every two to three days. Cells were then rinsed by PBS and fixed in 100% Ethanol for minimum 1 hr or maximum overnight at 4°C. Nodules formed by osteoblast were stained by Alizarin Red S (52). Briefly, cells after fixation were rinsed twice by PBS and incubated in 40mM alizarin red S pH 4.2 (Sigma) for 1hr at room temperature. Plates were washed with 95% ethanol on the shaker until solution became clear and air dried. The plates were then scanned using an Epson

Perfection 4990 Photo flatbed scanner (Epson Ltd, Herts, UK) and the percentage mineralisation area to the total area (Area Friction) was determined using Image J software (http://rsbweb.nih.gov/ij/). To normalize the results, the plates were re-hydrated using PBS and counterstained for 10-15 Sec with 0.1% Toluidine blue. The plates were scanned and the total areas covered by cells were quantified using Image J software. The mineralization results were then normalized to the Toluidine blue staining results of their relevant wells.

Primary Osteoclast isolation

Osteoclasts were derived from the mononuclear hematopoietic cell population from the long bone marrow of 10 weeks old female mice. Mononuclear cells were isolated using a modified protocol to that previously described (53). In brief, the bone marrow of limbs was flushed out by PBS using a syringe with 25-gauge needle. Cells were harvested by centrifugation and resuspended in the selection medium (Alpha-Minimal essential medium (α MEM) + GLUTAMAX™ (Gibco), 100 Units/mL Penicillin/100 µg/mL Streptomycin, 10% FCS, and 50ng/ml murine macrophage colony stimulating factor (M-CSF). The cells were then transferred into a T75 flask and incubated for 24 hours at 37°C, 5% CO_2 to allow the attachment of stromal cells. Non-adherent cells were collected by centrifugation and resuspended in growth medium (α MEM+GLUTAMAX™ containing 100 Units/mL Penicillin and 100 µg/mL Streptomycin, 10% FCS, 25ng/ml M-CSF, and 3ng/ml murine receptor activator of NF-κB ligand (RANKL) (R&D System)). The cells were then seeded onto glass coverslips ((Richardson's of Leicester) or dentine disks (www.dentinedisks.com) in 96-well plates at density of $1x10^6$ cells per well and cultured at 37°C, 7% CO_2 with the medium being replaced every 2-3 days. Cells on coverslips were cultured for 10 days and fixed in ice cold 10% buffered formalin, whereas cells on dentine disks were cultured for 17 days to allow time for resorption. Both coverslips and dentine disks were TRAP stained and counterstained by Gill's haematoxylin as described above (47). On coverslips, TRAP positive cells with more than 3 nuclei were quantified as osteoclasts. On dentine disks, the number of resorbing osteoclasts (defined as a TRAP positive cell in or in close proximity to resorption pits) and the amount of resorption per dentine disk were quantified by point-counting as previously described (54, 55).

365

366 TaqMan® Custom Array

367 Total RNA was isolated from both primary osteoblasts and long bone marrow with TRI Reagent
368 (Sigma) according to manufacturer's instruction. Extracted RNA was quantified using a NanoDrop®
369 ND-1000 Spectophotometer (The Thermo Scientific) and RNA quality was checked using an Agilent
370 2100 Bioanalyzer (Agilent Technologies). The cDNA was then synthesized using Promega ImProm-
371 II™ reverse trancriptase (Promega) with Oligo(dT) 15 primer (Promega) according to manufacturer's
372 instruction. An Applied Biosystems TaqMan custom array was used to validate the differential
373 expression of candidate genes. The quantitative RT-PCR amplification of the TaqMan arrays were
374 performed on an Applied Biosystems 7900HT Real-Time PCR system (Applied Biosystems) with
375 thermal cycling conditions: 2 mins at 50°C, 10 mins at 94.5°C, followed by 40 cycles of denaturation
376 at 97°C for 30 sec and extension at 59.7°C for 1 min (56). Data was collected and analysed using the
377 Applied Biosystems SDS 2.2.1 software (Applied Biosystems). In order to systematically compare all
378 target genes and limit interpolated errors, the same threshold values of 0.2 was used for each gene.
379 The data were then analyzed using the CT relative quantification method (33). Quantification of the
380 target cDNAs in all samples was normalized to the endogenous control gene: β-actin (Actb) ($\Delta CT = CT_{target} - CT_{Actb}$).
381 The difference in expression for each target cDNA between the WT and $P2Y_{13}R^{-/-}$
382 mice was expressed as ΔΔCT ($\Delta\Delta CT = \Delta CT_{WT} - \Delta CT_{P2Y13R-/-}$). Fold changes in target genes were
383 calculated by taking 2 to the power of the ΔΔCT ($2^{\Delta\Delta CT}$). Any genes with more than two folds
384 expression changes were recognized as significant variance (57). A heatmap showing gene expression
385 pattern variance was built from normalized ΔΔCT values, using the 'GenePattern' web software
386 (http://www.broadinstitute.org). Each colour patch in the heatmap represents the relative gene
387 expression level, with a continuum of expression levels from dark blue (lowest) to bright red (highest).
388

389 OVX surgery

390 OVX or sham-OVX (SHAM) surgery was performed on 16 weeks old, virgin, female WT and
391 $P2Y_{13}R^{-/-}$ mice (n = 7-9/group). OVX and SHAM surgery were performed as previously described

(58). Briefly, mice were anesthetized with 1.5-4% isoflurane in oxygen for surgery. The back of each mouse was shaved and surrounding area was cleaned with 70% ethanol. Dorsal incision was made through the skin in the region between the dorsal hump and the base of the tail. The ovaries, surrounding ovarian fat pad, and part of uterine horns under the abdomen wall were removed. For sham surgery, the ovaries and proximal parts of the uterine horns were exteriorised briefly then returned to the abdominal cavity before wound closure. Mice were euthanized for bone phenotype examination 4 weeks and 12 weeks after surgery to investigate bone phenotype changes.

Statistic analysis

All data are expressed as mean ± SEM. Statistical significance was tested for using either univariate analysis of variance or an unpaired Student's t-test using PASW Statistics (IBM, NY) and Prism 5 software (GraphPad, La Jolla).

Acknowledgements

The authors would like to thank the staff of the Bone Analysis Laboratory, The University of Sheffield for tissues processing and TRAP staining. This study was supported by the European Commission under the 7th Framework Programme (proposal #202231) performed as a collaborative project among the members of the ATPBone Consortium (Copenhagen University, University College London, University of Maastricht, University of Ferrara, University of Liverpool, University of Sheffield, and Université Libre de Bruxelles), and is a sub study under the main study "Fighting osteoporosis by blocking nucleotides: purinergic signalling in bone formation and homeostasis".

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579

TABLE. 1. Quantitative results of tibia bone parameters by µCT analysis.

	WT n=8	$P2Y_{13}R^{-/-}$ n=7	Means difference	P value summary
BMD (g/cm^3)	1.15 ± 0.007	1.15 ± 0.010	↑0.2%	
BV/TV	9.17 ± 0.340	5.73 ± 0.634	↓37.5%	C
BV (mm^3)	0.15 ± 0.006	0.09 ± 0.010	↓36.1%	C
BS/BV (1/mm)	87.26 ± 1.428	91.14 ± 3.226	↑4.5%	
Tb.Th (mm)	0.048 ± 0.0006	0.049 ± 0.0018	↑0.8%	
Tb.N (1/mm)	1.89 ± 0.054	1.18 ± 0.132	↓37.8%	C
Tb.Pf (1/mm)	26.18 ± 0.992	31.81 ± 1.607	↑21.5%	B
Tb.Sp (mm)	0.23 ± 0.003	0.33 ± 0.024	↑43.2%	C
DA	2.49 ± 0.078	1.94 ± 0.051	↓ 22.0%	C
SMI	2.13 ± 0.031	2.41 ± 0.074	↑13.0%	B
Ct.BV (mm^3)	0.83 ± 0.016	0.88 ± 0.029	↑7.1%	
Es. Dm (mm)	1.29 ± 0.028	1.32 ± 0.018	↑2.2%	
Ps.Dm (mm)	1.69 ± 0.029	1.71 ± 0.021	↑1.6%	

Values are mean ± SEM

[b] $p < 0.01$ (Student's unpaired t-test)

[c] $p < 0.001$ (Student's unpaired t-test)

List of Figure Legends

FIG.1. $P2Y_{13}R^{-/-}$ mice have reduced bone volume.

(A) 3D models of whole tibiae from $P2Y_{13}R^{-/-}$ and WT animals were constructed from μCT images. No obvious morphological differences were found between the $P2Y_{13}R^{-/-}$ and WT tibia, scale bar = 2.0mm. **(B)** 3D models of the trabecular region of the tibiae were constructed from μCT images, scale bar = 0.5 mm. **(C)** μCT data analysis showed $P2Y_{13}R^{-/-}$ mice had 5.5% less total tibial bone volume, **(D)** 37.5% less trabecular bone volume, and **(E)** 37.8% fewer trabeculae than WT mice. All values are mean ± SEM, $P2Y_{13}R^{-/-}$ n = 7, WT n = 8, ^{c} $p < 0.001$ (Student's unpaired t-test).

FIG.2. $P2Y_{13}R^{-/-}$ mice have reduced numbers of osteoclasts and osteoblasts on the endocortical bone surface.

Left tibiae were obtained from 16 week old female mice, sections prepared and TRAP stained as previously described (47). **(A)** Black arrows indicate TRAP positive osteoclasts on endocortical surface of both WT and $P2Y_{13}R^{-/-}$ mice, scale bar = 50 μm. **(B)** $P2Y_{13}R^{-/-}$ mice had 48.1% reduction in osteoclast numbers per mm endocortical surface (N.Oc/B.Pm = 2.8 ± 0.45 versus 5.4 ± 0.75, p = 0.0136)**. (C)** Cobblestone-like osteoblasts with large nuclei were also identified on endocortical surface and marked with black arrow heads, scale bar = 50 μm. **(D)** $P2Y_{13}R^{-/-}$ mice had 42.6% decrease in osteoblast number per mm endocortical surface (N.Ob/B.Pm = 9.1 ± 1.47 versus 15.9 ± 2.00, p = 0.0227) compared with WT controls. **(E)** TRAP positive osteoclasts (black arrowheads) and osteoblasts (black arrows) were identified on the trabecular surface of both WT and $P2Y_{13}R^{-/-}$ mice, scale bar = 50 μm. **(F)** $P2Y_{13}R^{-/-}$ mice had 22.9% decreased osteoblast numbers per mm trabecular bone surface (N.Ob/B.Pm = 13.5 ± 0.98 versus 17.4 ± 1.09, p = 0.0213). **(G)** There was no significant difference in osteoclast numbers on the trabecular bone surface (N.Oc/B.Pm =10.0 ± 1.39 versus 10.5 ± 0.47, p = 0.7587). All values are mean ± SEM, n = 6, ^{a} $p < 0.05$, ^{b} $p < 0.01$ (Student's unpaired t-test).

FIG.3. $P2Y_{13}R^{-/-}$ mice have reduced rates of bone formation in vivo

For dynamic histomorphometry, 16 weeks-old mice were given intraperitoneal injections of calcein (30 mg/kg) 14 days and 2 days prior to being euthanized. Right tibiae were obtained and LR White resin sections prepared. **(A)** First calcein label (white arrowheads) and second calcein label (white arrows) were both detected on the endocortical bone surface from both WT and $P2Y_{13}R^{-/-}$ mice. The average width between the labels (W) were measured and used to calculate mineral apposition rate. M: bone marrow; Ct: cortical bone; scale bar = 50 μm. **(B)** Mineral apposition rate was 49.7% less on the endocortical bone surface of $P2Y_{13}R^{-/-}$ mice tibia compared to WT (MAR = 1.53 ± 0.060 versus 3.03 ± 0.194, $p < 0.0001$). **(C)** Bone formation rate of $P2Y_{13}R^{-/-}$ mice was significantly decreased by 48.9% compared to WT (BFR = 1.09 ± 0.047 versus 2.13 ± 0.167, $p < 0.0001$). All values are mean ± SEM, n = 6, ^{c} $p < 0.001$ (Student's unpaired t-test).

FIG.4. $P2Y_{13}R^{-/-}$ mice have reduced osteoblast function and osteoclast formation in vitro due to altered expressions of key bone remodelling related genes

(A) Primary osteoblast cells isolated from neonatal mice calvariae of both WT and $P2Y_{13}R^{-/-}$ mice show no significant difference in proliferation. **(B)** $P2Y_{13}R^{-/-}$ osteoblasts showed a 50.1% reduction in mineralized area compared to osteoblasts from WT mice. **(C)** Representative whole well images of primary osteoblast cells cultured in differentiation medium for three weeks and stained with alizarin red S solution to reveal mineralisation, scale bar = 5.0 mm. All values are mean ± SEM, n = 3 repeat experiments with 12 replicates per experiment, ^{c} $p < 0.001$, (Univariate analysis of variance). **(D+E)** The number of osteoclasts (defined as TRAP positive cells (pink coloured) with three or more nuclei, black arrows), derived from M-CSF and RANKL treated $P2Y_{13}R^{-/-}$ mice bone marrow and cultured on glass coverslips, was 49.5% less than that from WT, scale bar = 50 μm. **(F+G)** There were 47.1% fewer resorbing osteoclasts [identified as TRAP positive cells (black arrows) in or in close proximity to resorption pits (white arrows)] formed from $P2Y_{13}R^{-/-}$ mice, scale bar = 100 μm. **(H)** This led to 66.1% less resorption on the dentine disks compared to WT osteoclasts. **(I)** There was no significant difference in the amount of resorption per resorbing osteoclast, $p = 0.4959$. All values are mean ± SEM, n = 4, each repeat contains 6 replicates, ^{c} $p < 0.001$, (Student's unpaired t-test). **(J+K)** The relative gene expression pattern variance was shown in a heatmap of normalized ΔΔCT values from

643 TaqMan custom array; each colour patch in the heatmap represents the relative gene expression level,
644 with a continuum of expression levels from dark blue (lowest) to bright red (highest). Compared to
645 WT primary osteoblasts, the expression of RhoA in $P2Y_{13}R^{-/-}$ osteoblasts was significantly down-
646 regulated while Tnfrsf11b (the gene for OPG) was up-regulated. Mapk3, Rock1, RhoA, and Tnfsf11
647 (the gene for RANKL) were significantly down-regulation in $P2Y_{13}R^{-/-}$ bone marrow samples
648 compared to WT. No other key regulatory genes had changes in expression levels.
649
650 **FIG.5. $P2Y_{13}R^{-/-}$ mice have a reduced estrogen deficiency-induced bone loss**
651 OVX surgery was performed on 16 week-old WT and $P2Y_{13}R^{-/-}$ mice. Mice were euthanized 4 and 12
652 weeks after surgery and right tibiae were isolated and examined using μCT (Skyscan 1172). The
653 response of $P2Y_{13}R^{-/-}$ mice to OVX was different for both BMD and trabecular thickness compared
654 with WT at both time points. **(A)** WT mice had a significant reduction in BMD 4 weeks and 12 weeks
655 after surgery, no significant reduction in BMD was observed in $P2Y_{13}R^{-/-}$ mice at 4 weeks and a
656 significant increase was observed at 12 weeks. **(B)** Trabecular thickness significantly decreased in
657 WT mice both at 4 and 12 weeks after surgery, no significant reduction in thickness was observed in
658 $P2Y_{13}R^{-/-}$ mice at 4 weeks and an increase was observed at 12 weeks. All values are mean ± SEM, n =
659 7-9, * $p < 0.05$ cf WT, *** $p < 0.0001$ cf WT; ^{a} $p < 0.05$ cf baseline, ^{c} $p < 0.0001$ cf baseline; (Student's
660 unpaired t-test).
661

662 Figure 1

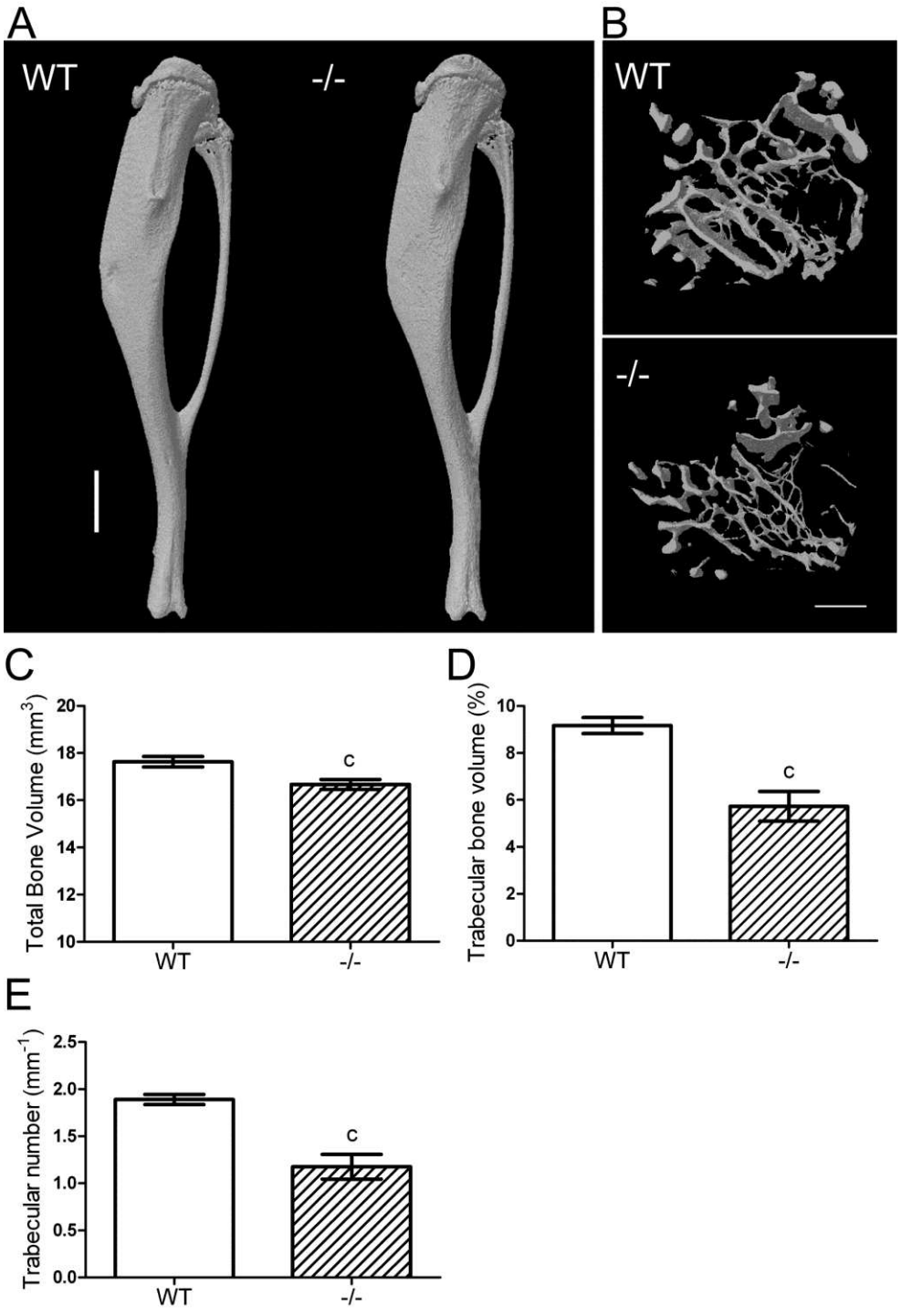

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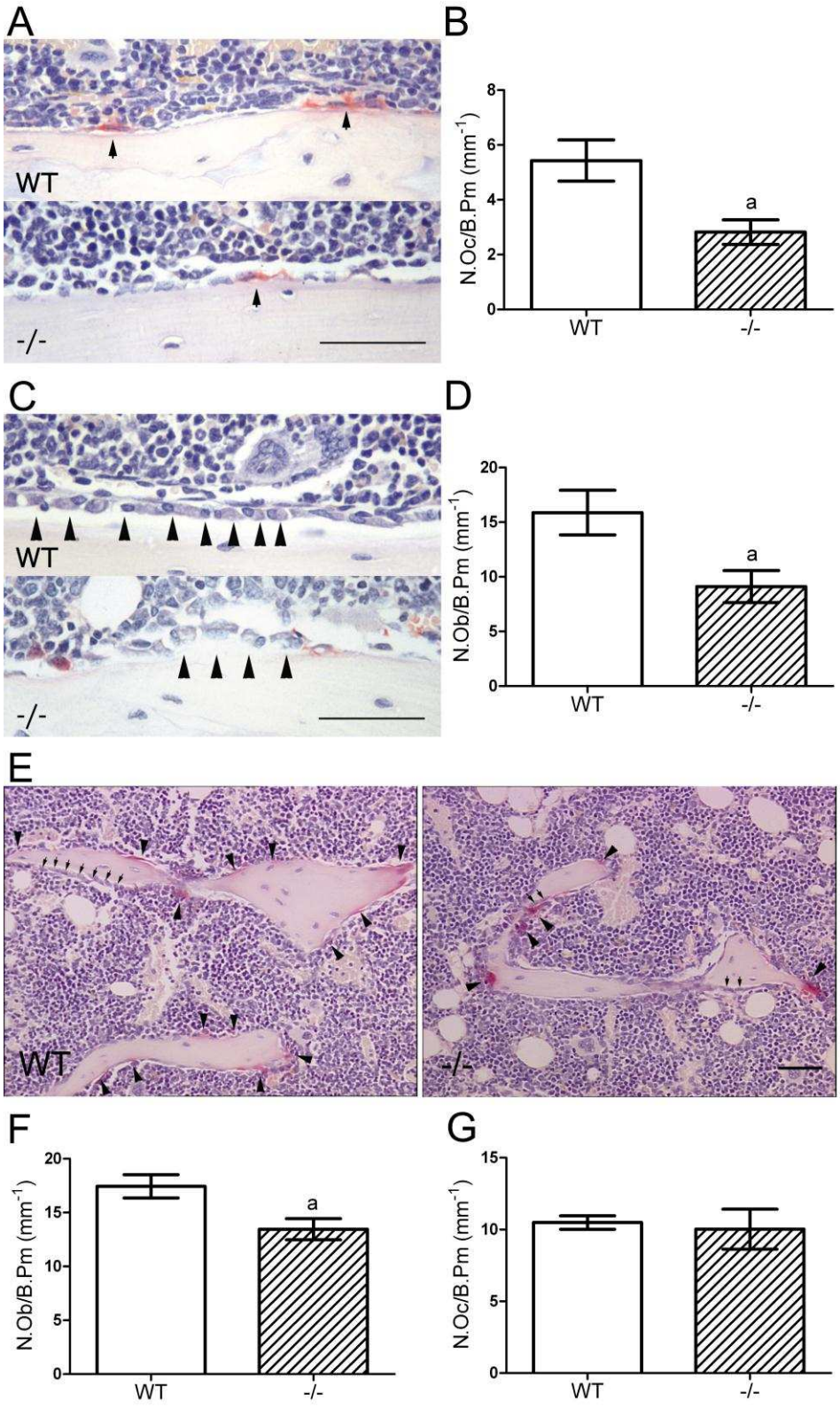
Figure 2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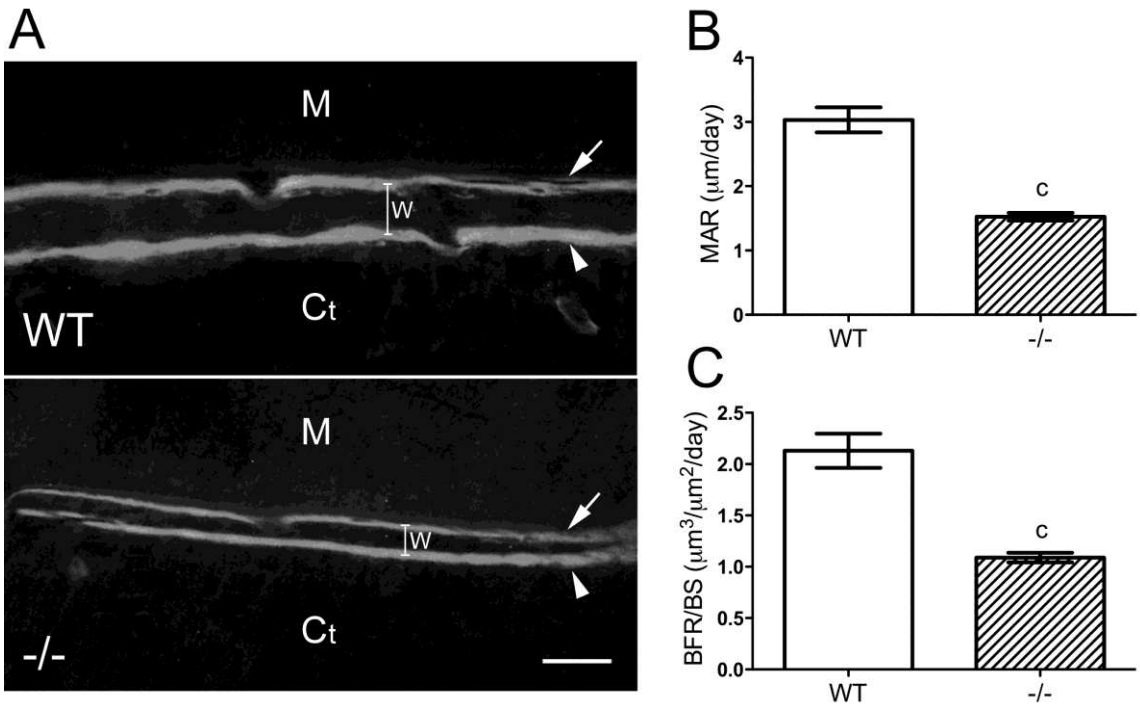
668 Figure 3



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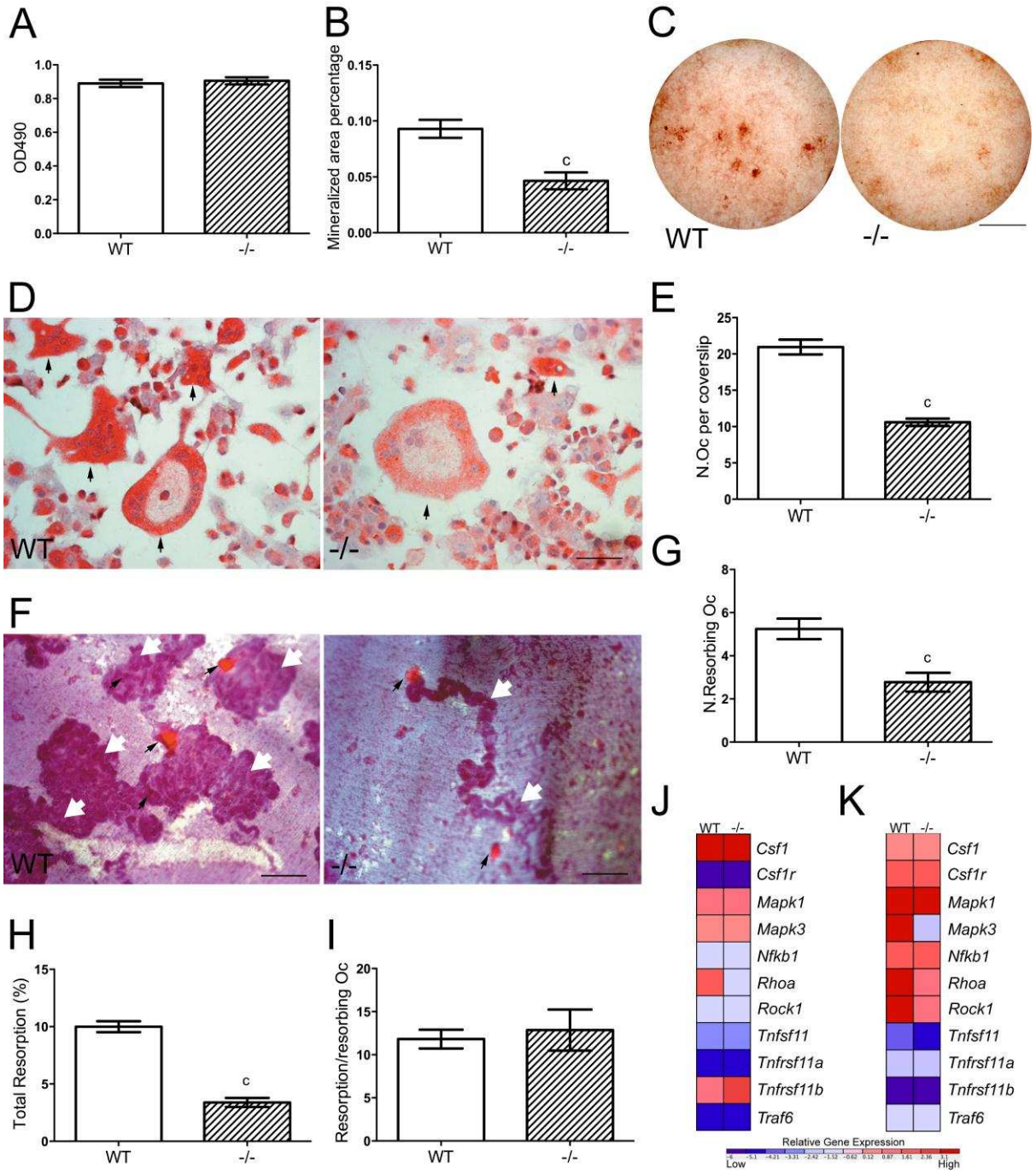
671 Figure 4



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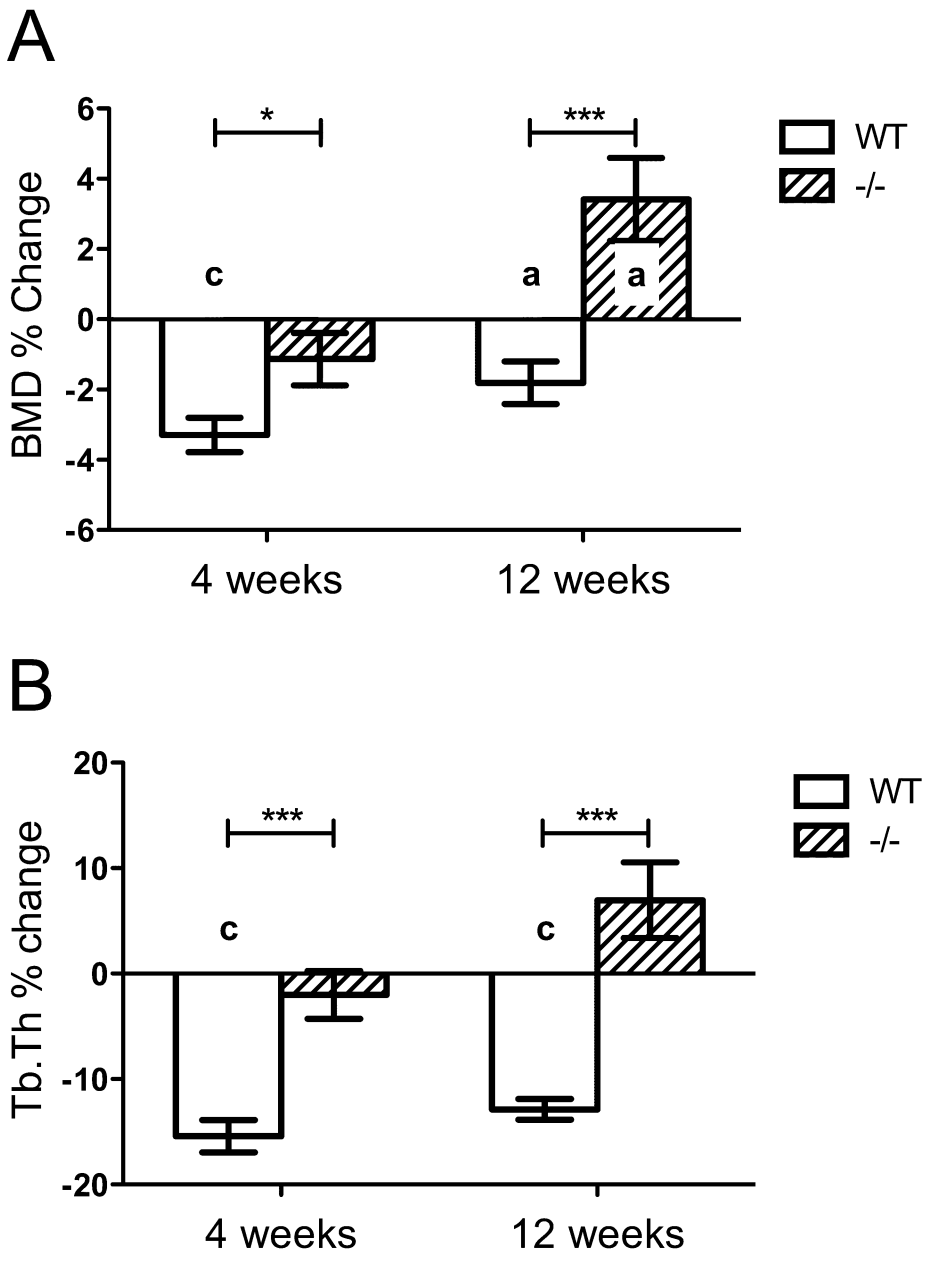
674 Figure 5



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