Loss of adenylyl cyclase 6 in leptin receptor expressing stromal cells attenuates loading-induced endosteal bone formation

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Abstract

Bone marrow stromal/stem cells represent a quiescent cell population that replenish the osteoblast bone-forming cell pool with age and in response to injury, maintaining bone mass and repair. A potent mediator of stromal/stem cell differentiation in vitro and bone formation in vivo is physical loading, yet it still remains unclear whether loading-induced bone formation requires the osteogenic differentiation of these resident stromal/stem cells. Therefore, in this study, we utilized the Leptin Receptor (LepR) to identify and trace the contribution of bone marrow stromal cells to mechanoadaptation of bone in vivo. 12 week old Lepr-cre;tdTomato mice were subjected to compressive tibia loading with an 11N peak load for 40 cycles, every other day for 2 weeks. Histological analysis revealed that Lepr-cre;tdTomato+ cells arise perinatally around blood vessels and populate bone surfaces as lining cells or osteoblasts before a percentage undergo osteocytogenesis. Lepr-cre;tdTomato+ stromal cells within the marrow increase in abundance with age but not following the application of tibial compressive loading. Mechanical loading induces an increase in bone mass and bone formation parameters, yet does not evoke an increase in Lepr-cre;tdTomato+ osteoblasts or osteocytes. To investigate whether adenylyl cyclase-6 (AC6) in LepR cells contributes to this mechanoadaptive response, Lepr-cre;tdTomato mice were further crossed with AC6fl/fl mice to generate a LepR+ cell-specific knockout of AC6. These Lepr-cre;tdTomato;AC6fl/fl animals have an attenuated response to compressive tibia loading, characterised by a deficient load-induced osteogenic response on the endosteal bone surface. This, therefore, demonstrates that Lepr-cre;tdTomato+ cells contribute to short term bone mechanoadaptation.

Keywords: stem cells, mechanobiology, bone adaptation, in vivo mechanical loading, adenylyl cyclase 6
1. Introduction

Physical loading is a potent regulator of bone anabolism, yet the cellular mechanisms by which this occurs are not fully understood [1, 2]. This mechanoadaptive response involves bone formation by osteoblasts which are derived from a progenitor or stromal cell population. The finite lifespan of the osteoblast suggests that these cells must be continuously replenished from a progenitor population to meet the cellular demand imposed by mechanical loading; a similar recruitment process operates in response to injury [3-7]. Although load-induced stromal/stem cell differentiation can be indirectly coordinated by the osteocyte [8], a recent study has demonstrated loading-induced bone formation in a bone explant model that is independent of apparent mechanical stimulation of osteocytes [9]. This indicates that applied mechanical stimulation may directly promote bone marrow stem/stromal cells (MSCs) osteogenesis [5, 10]. However, neither the load-induced MSC differentiation to osteoblasts nor the mechanistic basis for MSC mechanosensing has been fully elucidated *in vivo*.

The establishment of a robust MSC marker is critical for their identification and lineage tracing *in vivo*. MSCs are traditionally described as plastic-adherent, colony-forming, non-hematopoietic cells which can differentiate into chondrogenic, adipogenic and osteogenic progeny [3, 11]. Furthermore, MSCs are often perivascular *in vivo*, where murine MSCs are characterized by their lack of expression of hematopoietic (CD45) and endothelial markers (TER-119) and positive expression of Platelet-Derived Growth Factor receptor alpha (PDGFRα), Stem cells antigen-1 (Sca1), CD51, CD105, CD90, Nestin, aSMA, and combinations thereof [3, 12-14]. MSCs can therefore be retrospectively identified based on the above characteristics, yet an appropriate method for their prospective identification is lacking, and hence their location and physiological functions *in vivo* have remained elusive. Recently, Leptin Receptor positive (LepR⁺) cells were
identified as being perivascular and a major source of the Stem cell fraction (Scf) within the bone marrow [3, 15-19]. Additionally, these LepR+ cells were found to express the bone marrow MSC markers PDGFRα, and CD51 and to be highly enriched for fibroblast colony-forming units (CFU-F). Moreover, analyses indicated that LepR+ cells in the bone marrow largely overlap with Nestin, an intermediate filament protein that is known as a neural stem/progenitor marker in adult bone marrow [3, 20]. LepR+ cells not only express MSC markers but have now been shown to function as the main source of new osteoblasts and adipocytes in adult bone marrow and to be recruited to sites of injury to form bony ossicles that support haematopoiesis in vivo [3]. Also, osteogenic differentiation of these cells is increased following anabolic stimulation with parathyroid hormone [18]. Despite their presence in various tissues and organs [21, 22] and heterogenous nature [19], these characteristics suggest that LepR+ cells are a suitable candidate to determine the role of early progenitors in load-induced bone anabolic responses.

The candidature of these LepR+ cells as a means of prospectively identifying MSC fate is further supported by recent studies highlighting a role for the more committed osteoprogenitors in load-induced bone formation. Work by Liu et al. has focused on the effect of mechanical loading on primitive osteoprogenitors, looking specifically at Prrx1 (Paired related homeobox 1) and Sca1 positive cells [7], and Zannit et al. investigated the more committed osterix (Osx) positive osteoblast lineage cells [23]. Both report proliferation of these Prrx1+-Sca1+ and Osx+ cells following loading, however the role of Prrx1 has been predominately characterised on the periosteum.

The osteogenic differentiation of MSCs can be directly driven by mechanical loading in vitro [10, 24]. Furthermore, we have previously demonstrated that MSCs utilize adenylyl cyclases to generate cAMP as a second messenger in this mechanotransduction leading to osteogenesis [25].
Adenylyl cyclases (ACs) are a family of transmembrane enzymes that catalyze the cyclization of adenosine triphosphate (ATP) into cyclic adenosine monophosphate (cAMP) [26]. The AC family comprises nine distinct transmembrane isoforms (AC1-AC9), each with individual regulatory properties and restricted expression in only a limited number of tissues [27, 28]. Specifically, AC6 has been shown to be expressed in skeletal cells and is required for load-induced bone formation \textit{in vivo} [29]. Interestingly, skeletally mature mice, with a global deletion of AC6, did not present with a skeletal phenotype but formed significantly less bone than control mice in response to ulna loading, demonstrating that AC6 mediates bone mechanoadaptation [29]. While this study clearly demonstrates a role for AC6 in bone mechanobiology, given the global deletion of this enzyme, the specific cell type and mechanism of action of AC6 in bone mechanoadaptation remains unclear.

The development of the Lepr-cre mouse model along with specific deletion with Cre-lox recombination has provided a means to study the fate of these cells and the role of associated molecules. While LepR+ marrow stromal cells have been shown to be critical to adult bone formation, their role in mechanoadaptation is not known. Therefore this study aimed to characterise the response of LepR+ marrow stromal cells to load-induced bone formation, and to explore whether these cells or their progeny, contribute to load-related osteogenesis. Utilising \textit{Lepr-cre};\textit{tdTomato} mice, we have demonstrated that LepR+ cells arise perinatally in bone, appearing perivascularly before expanding with age to undergo osteoblastic and osteocytic differentiation and act as the main source of bone-forming cells. We have demonstrated that loading increases tibial bone formation and has little influence on the percentage of Lepr-cre;\textit{tdTomato}+ stromal cells within the morrow. Moreover, no significant changes in the percentage of Lepr-cre;\textit{tdTomato}+ cells lining bone surface or osteocytes were observed, suggesting that loading does not mediate the proliferation or recruitment of LepR+ cells.
Furthermore, our data show that AC6 deletion in LepR+ cells restricts the endosteal cortical bone response to loading, highlighting the contribution of LepR+ cells and a critical role for AC6 in bone mechanoadaptation. However, it is currently unclear whether LeprR+ cells are directly responsible for the anabolic bone response or LepR+ cells in the marrow contribute to the activation of non-Lepr-cre;tdTomato+ cells on the bone surface in a non-autonomous manner.

2. Materials and Methods

2.1. Mice

All transgenic mice were maintained in a C57BL/6 background. Transgenic mice B6.129-Leprtm2(cre)Rck/J JAX stock #008320 [21], B6.Cg-Ct(ROSA)26Sormt9(CAG-tdTomato)Hze/J JAX stock #007909 [30] and B6;129-Adcy6tm1.1Dek/J JAX stock #022503 [31] were purchased from Jackson Laboratories (Maine, USA), and rederived in-house. B6.129-Leprtm2(cre)Rck/J and B6.Cg-Ct(ROSA)26Sormt9(CAG-tdTomato)Hze/J were crossed to generate heterozygous B6.129-Leprtm2(cre)Rck/J and heterozygous B6.Cg-Ct(ROSA)26Sormt9(CAG-tdTomato)Hze/J breeding pairs. Female B6.129-Leprtm2(cre)Rck/J::B6.Cg-Ct(ROSA)26Sormt9(CAG-tdTomato)Hze/J offspring heterozygous for B6.Cg-Ct(ROSA)26Sormt9(CAG-tdTomato)Hze/J were used for all studies. This Lepr-cre;tdTomato mouse facilitates the labelling of cells actively expressing the Leptin receptor, in addition to their progeny irrespective of receptor expression. Heterozygous Lepr-cre;tdTomato mice were subsequently crossed with B6;129-Adcy6tm1.1Dek/J to generate animals with a knockout for AC6 in Lepr-cre;tdTomato expressing cells resulting in a Lepr-cre;tdTomato:AC60/0 mouse. Genotyping was achieved using DNA extracted from the ear and performed by Transnetyx (Cordova, TN, USA).

All animals were maintained in groups of 4 under specific pathogen-free conditions at 24°C ± 2°C.
with a 12-hour light/dark cycle and were provided with water and ad libitum diets. The procedures performed in this study were approved by Trinity College Dublin Animal Research Ethics Committee and Health Products Regulatory Authority in Ireland.

2.2. Histological analysis

Embryos, organs, and tibiae from all groups were dissected, fixed for 12 hrs in neutral buffered formalin (Sigma-Aldrich), decalcified in 10% EDTA (Sigma-Aldrich), and processed for standard paraffin embedding. Transverse 10µm sections were taken from individual samples and 2 sections were used in subsequent procedures. Prior to staining, sections were dewaxed and rehydrated. For haematoxylin and eosin (H&E) staining, sections were stained with HARRIS Hematoxylin solution (Sigma-Aldrich) for 4 min before rinsing and staining with Eosin Y solution (Sigma-Aldrich) for 2 min. Sections were subsequently rehydrated and mounted using DPX (Sigma-Aldrich). Slides were imaged on an Aperio Scanscope CS2 (Leica Biosystems). For immunofluorescence studies, bones tissue was fixed, decalcified and cryo-embedded. Sections of 20µm were sliced with a cryostat. DAPI at 1:2000 in PBS (Sigma-Aldrich) was applied to all samples for 5 min prior to sample mounting on glass slides using ProLong Gold mounting medium (Invitrogen). Leptin receptor staining was performed after antigen retrieval with proteinase K solution (20 minutes at 37° C) in a humidified chamber. Slides were then washed with PBS-Tween 0.5% v/v and blocked (5% BSA in PBS, 1 hour at 37° C). Slides were incubated in the primary antibody against leptin receptor (1:200, AF497, RnD Systems), washed and then in secondary antibody (1:500, Ab150129, Thermofisher). DAPI at 1:2000 in PBS was then applied before mounting using ProLong Gold mounting medium. Imaging was performed on the Leica SP7 (Leica Microsystems) scanning confocal microscope at 20x.
2.3. Flow cytometry

To quantify the percentage of Tomato+ cells in a given population, organs were harvested, minced and homogenized, and cell suspension filtered through a 70um cell strainer. After centrifugation, cell pellets were resuspended in red blood cell lysis buffer (20mM of Tris, 150mM of NH4Cl in diH2O), for 5 min on ice, then washed and resuspended in 1mL flow cytometry buffer composed of PBS (Sigma-Aldrich) with 0.5% BSA (Sigma-Aldrich) and 2mM EDTA (Sigma-Aldrich, pH7.2).

Left and right tibia were isolated, and the bone marrow was flushed from the marrow cavity with 3mL Dulbecco’s modified Eagle’s medium (DMEM, Sigma-Aldrich). Once flushed, cells were centrifuged at 400g for 5 min and re-suspended in 1mL red blood cell lysis buffer for 5 min on ice. Cells were washed before subsequent re-suspension in 2% Phosphate Buffer Saline (PBS)-Foetal Bovine Serum (FBS) and incubated on ice for 30 min. Cells were then incubated for 30 min on ice with CD45 (CD45-BV421, 563890, 1:100, BD Biosciences) and TER-119 (TER-119-BB515, 564760, 1:100, BD Biosciences) antibodies. After washing in PBS, cells were re-suspended in 1mL flow cytometry buffer. Flow cytometry analysis was performed on a BD LSRFortessa (BD Biosciences) at medium speed and gated at 100,000 events of Tomato+ cells.

2.4. In vivo axial tibia loading

Mice at 12 weeks of age were initially anesthetised using 4% isoflurane and were then maintained at 1.5-2% isoflurane during the remainder of the procedure. The right tibia was placed between 2 cups attached to an electromagnetic loading system with feedback control (ElectroForce 5500, TA
Instruments). After an initial 2N load, a peak compressive load of 11N was applied, for 40 cycles with 10 seconds of rest between each cycle, every second day, for 2 weeks as previously described [32]. Left tibiae served as non-loaded internal controls. Body weight was measured at 12 weeks of age and on subsequent loading days. All animals were euthanized on day 18 and prepared for either dynamic histomorphometric, histological or flow cytometry analysis.

2.5. Micro-computed tomography (µCT) analysis

Mice were placed under isoflurane-induced anaesthesia as described above. Tibiae were imaged by *in vivo* micro-CT (Scanco VivaCT 80; Scanco Medical AG). The cortical area was scanned with a voxel size of 25 µm. Scans were performed using a voltage of 70 kVp, a current of 114 µA and a 200ms integration time. A Gaussian filter (sigma = 0.8, support = 1) was used to suppress noise and a global threshold of 150 was applied for analysis or cortical bone scans. The bone volume, cortical area and thickness, second moment of area around major/minor ($I_{min}$ and $I_{max}$) were quantified using scripts provided by Scanco.

Whole-body scans were taken for phenotypic analysis of *Lepr-cre;tdTomato;AC6^[08]* mice. Briefly, after euthanasia, whole-body scans were performed at 15 µm voxel size. Scans were performed using a voltage of 70 kVp, a current of 114 µA and a 200ms integration time. A Gaussian filter (sigma = 0.8, support = 1) was used to suppress noise and a global threshold of 150 was applied to generate the 3D reconstruction using scripts provided by Scanco.

Whole bone analysis was performed on datasets derived from CT scans using BoneJ [33] (version 1.4.2), an ImageJ plugin. Following segmentation and removal of fibula from the dataset, a minimum bone threshold was selected using a histogram-based method in ImageJ which utilises...
all pixels in a stack to construct a histogram and was further confirmed using ImageJ “threshold function”. A threshold of 100 was applied to all datasets to separate higher density bone from soft tissues and air. This threshold was used in “Slice Geometry” function within BoneJ to calculate bone cross-sectional area (CSA), second moment of area around the minor axis ($I_{\text{min}}$), second moment of area around the major axis ($I_{\text{max}}$), mean thickness determined by local thickness in two dimensions (Ct.Th), ellipticity and predicted resistance to torsion (J). The most proximal (0 - 15%) and the most distal portions (85 - 100%) of tibial length were excluded from analysis, as these regions include trabecular bone.

2.6. Dynamic histomorphometry

Mice were injected with calcein (15 mg/kg body weight; Sigma-Aldrich) on the third and sixth day of loading. Left and right tibiae were isolated, cleaned of soft tissue, fixed in formalin (Sigma-Aldrich) and stored in 70% EtOH for dynamic histomorphometry. The tibiae were dehydrated in graded alcohol (70–100%), infiltrated with three changes of Technovit 9100 methyl methacrylate (CN Technical Services Ltd), and embedded in Technovit 9100 following manufacturer recommendation. Transverse sections of the embedded tibia midshaft were imaged on a Leica SP7 (Leica Microsystems) scanning confocal microscope. Measurements of the bone perimeter, single label perimeter, double-label perimeter, and double-label area were completed with Fiji [34] (version 1.6.0_24) and used to calculate mineralizing surface/bone surface (MS/BS), mineral apposition rate (MAR) and bone formation rate/bone surface (BFR/BS). Measurements were taken at both the endosteum and periosteum.
2.7. Immunofluorescence image analysis

A region of interest for cortical bone spanning 100 slices (2500µm) was selected 3mm from the tibia-fibula junction towards the tibial proximal metaphysis. Using Fiji, the length of the bone surface covered by Tomato\(^+\) cells at both endosteal and periosteal surfaces, and the number of Tomato\(^+\) cells embedded within bone were counted within the region of interest.

To determine if endosteal regions showing bone formation by dynamic histomorphometry correlate with regions where Tomato\(^+\) cells are observed on confocal images, both sets of images were analysed with Fiji. In order to compare between different animals, the total length of the endosteum was measured and expressed in percentage (0% starting in regard of the tibial ridge, going clockwise to 100%). Locations, where one or two labels of calcein are observed, were determined and plotted against the total length of the endosteum for static and loaded bones. Then, the presence of tdTomato\(^+\) cells along the endosteum was observed and plotted against the total length of the endosteum. Results were averaged and pooled in clusters of 5%.

2.8. Statistical analysis

For flow cytometry of different tissues, a one-way ANOVA analysis was performed with Tukey correction. Dynamic histomorphometry analysis of Lepr-cre;tdTomato;AC6\(^0\)/\(^n\) and comparison with wild-type mice was performed with a two-way ANOVA with Tukey correction. For all other studies, unpaired two-tailed student t-test with Wilcoxon correction was employed. Data were analysed using Graph Pad Prism 8 and for gross cortical bone morphology analysis, graphs were plotted using programming language ‘R’, version 3.1.3 (R Foundation for Statistical Computing,
Vienna, Austria; http://www.r-project.org). The number of animals is detailed in captions with each figure. In all experiments, p<0.05 was considered statistically significant.

3. Results

3.1. LepR+ bone marrow cells are the main source of bone forming cells on the early endosteal surface and later periosteal surface in addition to embedded osteocytes.

We first analysed the spatiotemporal expression of LepR+ cells in our model. Tomato+ cells were identified prenatally at E19.5 in the brain and ossification zone of the radius, ulna and tibia (Figure S1). The pattern of Tomato+ cells was further investigated in all major organs post-natally (Figure S2). H&E staining was used to investigate the anatomy of organs, and to more accurately identify the location of Tomato+ cells at 8- and 12-weeks of age (Figure S2 A-F). Tomato+ cells were found in various organs including the liver, kidney medulla, lung, spleen, and heart (Figure S2 A-B, D-F). Tomato+ cells increased with age, from 8- to 12-weeks, in each of these organs. Quantification of cell number within each organ of the Lepr-cre;tdTomato mouse was performed using flow cytometry at 12-weeks which further highlighted the spatial differences in Tomato+ cells. At 12 weeks of age, Tomato+ cells accounted for less than 7% of cells in each organ with the exception of the liver where 38% of cells were Tomato+.

The expression of Lepr-cre;tdTomato+ cells in 8- and 12-week old mice was analyzed in greater detail within the tibiae. Sagittal sections of the tibia were imaged using confocal microscopy and the trabecular and cortical bone regions examined for patterns of Tomato+ cell expression (Figure 1). Firstly, investigating the trabecular region of the tibia of 8-week old Lepr-cre;tdTomato mice,
revealed the presence of Tomato+ cells within the marrow space between trabeculae (Figure 1Bi-Cii) where these cells located around sinusoids (Figure 1 Bii). Small populations of Tomato+ cells were also found lining and embedded within trabecular struts (Figure 1 Bi, Ci & Dii). While Tomato+ cells are located perivascularly and along the bone surface, no Tomato+ cells were found in the growth plate (Figure 1 Di). By 12- weeks of age, the prevalence of Tomato+ cells located perivascularly within the trabecular bone marrow increased (Figure 1 Ei-ii), while Tomato+ cells also increased along and within the trabecular bone. Interestingly, at 12 weeks of age, these cells along the surface of trabecular bone morphologically resembled that of osteoblasts (cuboidal) and bone lining cells (flattened)(Figure 1 F, yellow arrows) suggestive of osteoblastic differentiation of LepR+ bone marrow stromal cells. Furthermore, the population of Tomato+ cells embedded within the trabecular bone (Figure 1 F, green arrows) is evidence of osteocytic differentiation.

Examining the cortical bone region of the tibial mid-diaphysis, a small population of Tomato+ cells were found perivascularly within the marrow and along the bone surface at 8-weeks of age (Figure 2 A). The pattern of expansion of this cell population seen in trabecular bone also holds true when the cortical bone was further examined (Figure 2 B-D); at 12 weeks, Tomato+ cells are found perivascularly, along the endosteal surface (Figure 2 Cii & D, yellow arrow) and embedded within the cortical bone (Figure 2 D, green arrows). This observation was confirmed using flow cytometry, which showed that the percentage of Tomato+ cells in the marrow is 3.41% ±2.50 in the tibia and 3.02% ±1.98 in the femur in 12-week old mice (Figure 2 E). Furthermore, LepR+CD45-Ter119 bone marrow stromal cells accounted for 0.16% ±0.11 of bone marrow cells within the tibia (Figure 2 F). Together, these data suggest that Lepr-cre;tdTomato+ bone marrow stromal cells appear perivascularly, where they expand with age, are recruited to the bone surface of both trabecular and cortical bone and undergo osteoblastic and osteocytic differentiation.
3.2. Tibia loading enhances endosteal and periosteal cortical bone formation

To investigate whether there are changes in the LepR⁺ stromal cell pool and their progeny during loading-induced bone formation, a compressive load of 11N was applied to the tibia of 12-week old female Lepr-cre;tdTomato mice (Figure 3 A-C). Consistent with previous studies, our data show that tibia loading in this model leads to an anabolic response in cortical bone of Lepr-cre;tdTomato mice (Figure 3 D-F). Analysis of the entire tibial cortex by micro-CT reveals an increase in cross-sectional area following loading, as well as a greater cross-sectional ellipticity (Figure 3 D). The second moment of inertia around the major (Iₘₖᵢₙ) and minor (Iₘₖ₉ₐₓ) axes and the predicted resistance to torsion (J) are also enhanced following the 2 weeks of loading in Lepr-cre;tdTomato mice (Figure S4).

Bone formation was also measured on both the endosteal and periosteal surface using dynamic histomorphometry, where right (loaded) tibiae formed significantly more bone than left (non-loaded) tibiae (Figure 3 E,F). After 2 weeks of loading, we found a significant increase in mineralised surface, mineral apposition rate and bone formation rate at both the endosteal (Figure 3 E) and periosteal surfaces (Figure 3 F). Mineralised surface, mineral apposition rate and bone formation rate were increased by 30, 20, and 79% on the endosteal surface, respectively (Figure 3 E), while on the periosteal surface mineralised surface, mineral apposition rate and bone formation rate, increased by 23, 10, and 28%, respectively (Figure 3 F).

3.3. Tibial loading does not influence the number of LepR⁺ bone marrow stromal cells nor their progeny
To determine whether these load-related increases in cortical bone formation are linked to an expansion and differentiation of the Lepr-cre;tdTomato+ marrow stromal cell population, bone marrow was flushed from the loaded and non-loaded tibiae and flow cytometry was performed to assess the percentage of Tomato+ cells. The percentage of Tomato+ cells did not increase following tibia loading when no cellular sub-groups were excluded (Figure 4 A). However, when the CD45+ hematopoietic and TER-119+ erythropoietic cells were excluded, the percentage of Tomato+ stromal cells was found to be slightly greater (Figure 4 B). While not significant, this could be indicative of a proliferative response in these primitive Tomato+ cells. Interestingly, additional staining of LepR (Figure S3) reveals a colocalization of the signals from tdTomato+ and LepR antibody only in the marrow; Tomato+ cells lining bone surfaces and Tomato+ osteocytes do not show immunolabelling for LepR, demonstrating that they are not actively expressing LepR at the time of tissue collection on D17.

The effect of loading on the numbers of Tomato+ cells, either lining or embedded within bone, which originated from LepR+ stromal cells was furthered assessed using histology (Figure 4 C). No change in the percentage of Tomato+ cells lining the endosteal or periosteal surface or in the cells embedded in the bone as osteocytes was observed in response to tibial loading (Figure 4 D). The location of Tomato+ cells lining the endosteal surface was further analysed and compared to the location where active bone formation had been detected by dynamic histomorphometry (Figure 4 E). This revealed that areas of endosteal surface where active bone formation ranged from 25-45%, 55-70% and 80-95% (Figure 4 E, upper graph) failed to exhibit any correlative difference in the local number of Tomato+ cells (Figure 4 E, lower graph).

These data demonstrate that our loading protocol which increases bone formation, does not significantly induce proliferation of LepR+ bone marrow stromal cells. Moreover, there is no
recruitment of this cell type to the bone surface, suggestive that a re-activation of the cells already present at this location are responsible for the increased load-related bone accrual response.

3.4. LepR$^+$ cells play a role in loading-induced bone formation via an adenylyl cyclase 6 dependent mechanism

To investigate whether cells derived from LepR$^+$ stromal cells play a role in load-induced bone formation, we crossed the Lepr-cre;tdTomato mouse with adenylyl cyclase 6 floxed animal ($AC6^{fl/fl}$) to generate an AC6 knockout in Leptin receptor expressing cells and their progeny (Lepr-cre;tdTomato;AC6$^{fl/fl}$). Utilising a global deletion of Adenylyl Cyclase 6, it has been previously shown that AC6 is required for loading-induced bone formation [29]. However, it is unclear in which cell type AC6 is mediating this response. Lepr-cre;tdTomato;AC6$^{fl/fl}$ mice are healthy and fertile and appeared phenotypically normal (Figure 5 A & B, Figure S5). Body weight of all mice in the study increased with age, with no differences observed between Lepr-cre;tdTomato control animals and Lepr-cre;tdTomato;AC6$^{fl/fl}$ mice at any time point (Figure S5 A). On average the body weights of Lepr-cre;tdTomato and Lepr-cre;tdTomato;AC6$^{fl/fl}$ mice were not significantly different at 8- or 12-weeks of age, where Lepr-cre;tdTomato mice weighed 17.0 ±0.1g and 18.9 ±0.4g at 8- and 12-weeks, respectively, whereas Lepr-cre;tdTomato;AC6$^{fl/fl}$ mice weighed 17.7 ±0.4g and 19.0 ±0.8g at 8- and 12-weeks, respectively (Figure S5 A). In addition, µCT analysis was conducted to further examine cortical bone microarchitecture of Lepr-cre;tdTomato;AC6$^{fl/fl}$ and Lepr-cre;tdTomato mice tibiae. The total area, cortical area, cortical thickness, $I_{\text{min}}$, and $I_{\text{max}}$ at the tibial midshaft of Lepr-cre;tdTomato;AC6$^{fl/fl}$ mice were not significantly different from Lepr-cre;tdTomato mice (Figure 5 C). Collectively, these data indicate that there were no differences in the skeletal morphology of young adult Lepr-cre;tdTomato and Lepr-cre;tdTomato;AC6$^{fl/fl}$ mice.
Thus, these results suggest Lepr-cre;tdTomato;AC6^{fl/fl} mice do not exhibit a gross morphological or skeletal phenotype, which is consistent with the AC6 global deletion model [29].

As there is no skeletal phenotype following AC6 deletion, an identical tibial loading regime was applied to the Lepr-cre;tdTomato;AC6^{fl/fl} mice and µCT measurements were taken along the entire tibia length at the end of the loading period (Figure 6 A). Interestingly, no changes were observed for tibial cross-sectional area, ellipticity (Figure 6 A), thickness of the cortical bone, $I_{min}$, $I_{max}$ or the resistance to torsion (Figure S7) following application of load in these Lepr-cre;tdTomato;AC6^{fl/fl} mice. This result demonstrates that the deletion of AC6 in a LepR specific manner prevents the load-induced cortical bone formation otherwise observed.

Dynamic histomorphometry was utilised to further evaluate the effect of loading on cortical bone formation in Lepr-cre;tdTomato;AC6^{fl/fl} mice (Figure 6 B, C). No changes in mineralised surface, mineral apposition rate or bone formation rate were found at the endosteal surface of tibial cortical bone in Lepr-cre;tdTomato;AC6^{fl/fl} post-loading (Figure 6 B) which is in agreement with µCT analysis. However, on the periosteal surface, loading of Lepr-cre;tdTomato;AC6^{fl/fl} tibia resulted in an increase in mineralised surface and bone formation rate, while no change in mineral apposition rate was detected (Figure 6 C).

This effect of loading on Tomato^{+};AC6^{-/-} cells lining and embedded within bone was furthered assessed using histology (Figure 7 A). Mechanical loading did not change the percentage of Tomato^{+};AC6^{-/-} cells observed in any region of the tibiae (Figure 7 B). The percentage of Tomato^{+};AC6^{-/-} cells on the endosteum, periosteum and embedded within the cortical bone were investigated, and no effect of loading on cell number was evident. These data demonstrate that Lepr-cre;tdTomato;AC6^{fl/fl} animals have both an attenuated endosteal osteogenic response to loading and exhibit no change in the percentage of local Lepr-cre;tdTomato^{+} cells. This, therefore,
indicates that LepR$^+$ cells contribute to bone formation on the endosteal surface and that adenylyl cyclase 6 is required in these cells to mediate this response.

4. Discussion

Bone marrow stromal/stem cells represent a quiescent cell population that supply bone-forming osteoblast cells to maintain tissue homeostasis and to facilitate repair in response to injury. A potent mediator of stromal/stem cell differentiation in vitro and bone formation in vivo is mechanical loading, yet it is unclear whether load-induced bone formation requires the recruitment and differentiation of resident progenitor cells. Therefore, in this study, we utilized the Leptin Receptor to identify and trace the contribution of bone marrow stromal cells and their progeny to bone mechanoadaptation. Lepr-cre;tdTomato$^+$ cells were tracked from E19.5 through to early adulthood, to find that Lepr-cre;tdTomato$^+$ cells initially appear perivascularly within the marrow, perinatally, and increase in number with age, contributing to osteoblast and osteocyte populations demonstrating osteogenic lineage commitment. Compressive loading of Lepr-cre;tdTomato tibiae resulted in increased bone formation on the endosteal and periosteal surface of cortical bone. Interestingly, no significant increase in the percentage of Lepr-cre;tdTomato$^+$ stromal cells within the bone marrow was observed, while no significant changes in the number of Lepr-cre;tdTomato$^+$ cells lining the bone surface or osteocytes embedded in bone were found following loading. AC6 deletion in Lepr-cre;tdTomato$^+$ cells resulted in a reduced endocortical bone-forming response to loading, demonstrating a critical role for Lepr-cre;tdTomato$^+$ cell progeny in loading-induced bone formation. In summary, these data indicate that mechanical loading does not result in the proliferation of Lepr-cre;tdTomato$^+$ stromal cells within the marrow nor the recruitment of these cells to the bone surface, suggesting that these cells may play either a supportive role in
osteogenesis via cell non-autonomous effects or alternatively Lepr+ cells already present along the bone surface are re-activated, mediating short term load-induced bone formation in a manner that is dependent on AC6.

Leptin Receptor is expressed prenatally in bone and brain tissue and becomes widely expressed in nearly all major organs postnatally. Using confocal microscopy, the expression pattern of Lepr-cre;tdTomato+ cells was analyzed in E19.5 mice. During this late stage of gestation, a limited number of Lepr-cre;tdTomato+ cells were found to be present only in the brain and bone tissue. This is consistent with previous work that demonstrated no Lepr-cre;tdTomato+ cells in the ossification centre of bone at E15.5 [20], and limited LepR positive cells at E19.5, indicating little contribution of these cells to bone formation at these earlier stages of development [3]. The number of Lepr-cre;tdTomato+ in the metaphyseal bone marrow showed a sharp increase by postnatal day P0.5 [3], and in 1-week old mice LepR+ cells were present throughout the bone marrow [20]. Our data, in combination with previous work, suggest that Lepr-cre;tdTomato+ cells increase in the bone marrow during bone maturation. We have also shown that Lepr-cre;tdTomato+ cells were present within the brain at E19.5 and are found in the heart, lungs, spleen, liver and the medulla region of the kidney in 8- and 12-week old animals. Further interrogation by mRNA expression analysis of LepR in various mouse tissues also found that the heart and spleen have the lowest expression of LepR, of the tissues analysed [22], which is consistent with our findings. This wide expression of Leptin Receptor has considerable implications for the use of the Leptin Receptor for the study of MSC behaviour in bone, particularly when combined with Cre-lox strategy for gene deletion.

Within bone, Lepr-cre;tdTomato+ cells appear perivascularly in the marrow, where they are recruited to the bone surface and commit to the osteogenic lineage with age. The percentage of
Lepr-cre;tdTomato+ cells within the tibial marrow increased between 8- and 12-weeks of age suggesting an maturation-related expansion of this cell type. This increase in marrow Lepr-cre;tdTomato+ cells was mirrored by an increase in tdTomato+ cells on both bone surfaces and embedded with bone. Similar findings were reported by Zhou et al. where the percentage of Lepr-cre;tdTomato+ cells making up Col2.3-GFP+ osteoblast cells increased from 10% to 81% from 6- to 14-months of age [3]. This earlier study also reported that the increase found was not due to the induced expression of LepR at this age, but rather the proliferation and differentiation of LepR cells resident in the bone marrow [3]. Furthermore, we did not observe LepR immunolabelling in cells located on the bone surface or embedded in the bone matrix in our Lepr-cre;tdTomato mice, and studies at 15-weeks in the same mouse model have shown that tdTomato+ cells in the bone tissue were osteocalcin- and dentin matrix protein 1 (DMP1)-expressing mature osteoblasts and osteocytes, respectively [20]. Importantly, LepR mRNA was not detectable by quantitative real-time PCR in the osteoblasts, suggesting that Lepr-cre;tdTomato+ mature bone cells do not autonomously express LepR, but are descendant of LepR+ precursors [20]. Taken together, these data demonstrate that the Leptin Receptor is a robust marker of MSCs in vivo to trace their progeny.

While the contribution of Lepr-cre;tdTomato+ cells to the adult bone formation has been investigated, their contribution to load-induced bone formation has not been examined to date. Herein, in vivo mechanical loading of Lepr-cre;tdTomato mouse tibia resulted in no change in the percentage of Lepr-cre;tdTomato+ cells along the bone surface or osteocytes, suggesting that this loading protocol does not initiate recruitment of Lepr-cre;tdTomato+ marrow cells, but instead activates resident cells at the bones surface. This is close agreement with several previous observations made in other models of bone loading where both early loading-related activation of osteoblast metabolic activity were observed and where there was evidence for the direct
transformation from quiescence to bone formation in the adult periosteum following a single brief period of bone loading[35, 36].

The loading protocol used in this study spanned two weeks in length, therefore, while loading induced a trend to an increase in the percentage of Lepr-cre;tdTomato+ marrow stromal cells, these LepR+ progenitor cells do not contribute to bone formation within the time frame studied. Recent work from Yang et al. also found a lack of response in this cell population following 10 days of iPTH treatment in the femoral marrow [18]. Interestingly, this finding of reactivation of mature cells is consistent with a study by Chow et al., where loading of the caudal vertebrae resulted in reactivation of previously quiescent bone-lining cells [37]. As with the present study, the rapidity with which new bone was formed following mechanical stimulation raised the potential for this bone formation to occur via the reactivation of cells already along the bone surface, rather than recruitment from the stem cell niche. More recently, Matic et al. demonstrated that labelled bone surface cells were observed at time points extending beyond the reported lifespan for an osteoblast, suggesting continuous reactivation of bone lining cells is a potential mechanism of adult bone adaptation [38]. Other recent studies have reported proliferation of osteoprogenitor (Prrx1+Sca1+ [7]) and pre-osteoblast (Osx+ [23]) cells as a major contributor to loading-induced bone formation and not the differentiation of stem cells, which further strengthens our findings.

The specific knockout of AC6 in LepR+ cells does not induce a skeletal phenotype but results in abolition of load-induced adaptive responses at the endocortical surface, demonstrating a critical role for LepR+ cells and their progeny in bone mechanoadaptation. The absence of a basal skeletal phenotype in Lepr-cre;tdTomato;AC6fl/fl mice suggests that AC6 does not play a role in skeletal development. However, the disruption of bone mechanoadaptation on the endosteal surface in Lepr-cre;tdTomato;AC6fl/fl mice demonstrates the importance of AC6 in load-induced bone
formation. At the time of loading, approximately 50% of the bone surface is covered by cells
derived from LepR$^+$ cells, these cells may be responsible for the anabolic bone response and this
is consistent with our *in vitro* studies highlighting a vital role for AC6 in MSC and mature bone
cell mechanotransduction [25, 29]. However, we cannot yet directly rule out the possibility that
LepR$^+$ cells in the marrow may contribute to the activation of non-Lepr-cre;tdTomato$^+$ cells on the
bone surface in a non-autonomous manner.

While the response on the periosteal surface was blunted, the bone-forming response observed at
this location may be attributed to other non-LepR$^+$ cells potentially recruited from the periosteum
[39]. For example, Duchamp de Lageneste *et al.* described a population of skeletal stem cells
labelled by Prrx1$^+$ in the periosteum that expressed markers shown to define mouse skeletal stem
cells, but were negative for leptin receptor[39]. Moreover it was demonstrated by Moore *et al.*, that Prrx1$^+$ cells resident in the periosteum can sense and respond to physical stimulation *in vivo*
and contribute to the load-induced bone formation[40]. Additional work is required to draw
conclusive findings, however in our experiment this Lepr$^+$/Prrx1$^+$ cell population, would not be
targeted by the AC6 deletion, and thus may play a role in the load-induced bone-forming response
observed on the periosteal surface.

This diminished mechanoadaptive response is in agreement with work examining a global
knockout of AC6, where AC6 deletion resulted in an inhibited response to ulna loading [29], and
further strengthens the potential involvement of the primary cilium, to which AC6 localises, in
bone mechanoadaptation [41, 42]. Furthermore, as with the Lepr-cre;tdTomato mouse, no change
was found in the percentage of Lepr-cre;tdTomato$^+$ cells on the bone surface, nor embedded within
the bone. The lack of bone formation, and the failure of loading to induce migration of LepR$^+$ cells
from the marrow to the bone surface in Lepr-cre;tdTomato;AC6$^{fl/fl}$ mice is consistent with our
hypothesis that loading induced bone formation occurs via Lepr-cre;tdTomato+ cells, and that this process requires AC6.

5. Conclusion

In conclusion, this study has characterised the contribution of LepR+ bone marrow stromal cells to bone formation during growth and in response to mechanical loading. Interestingly, although LepR+ stromal cells are the main source of osteoblasts and osteocytes with age, they are not recruited to the bone surface in response to short-term loading. Rather, LepR+ cell contribute to bone formation either through a supportive role via cell non-autonomous effects or alternatively LepR+ cells already present along the bone surface are re-activated. Interestingly, this activation required AC6 which has previously been shown to be an important component of stem cell and mature bone cell mechanotransduction.

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Author’s roles

DAH is responsible for the experimental concept and objectives. MR, GPJ and DAH designed the experiments. GPJ and MR performed the experiments and collected the data. GPJ, MR, MMO and BJ analysed the data. GPJ, MR, BJ, AAP and DAH interpreted the data. Approving final version of manuscript: MR, GPJ, MMP, BJ, AAP and DAH.
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Figure 1: tdTomato+ bone marrow cells appear around sinusoids and contribute to osteoblast and osteocyte populations over time in trabecular bone. To assess whether \textit{LepR-cre} was actively expressed in adult tibia, limbs were harvested from 8- and 12-week-old \textit{Lepr-cre;tdTomato} mice and processed for histological analyses with the nuclear dye DAPI. (A) Representative image of 8- and 12-week-old \textit{Lepr-cre;tdTomato} mice tibia. tdTomato+ cells / DAPI.
an 8-week old tibia, showing regions of interest. (B-D) Confocal microscopy revealed tdTomato+ signal in 8-week old trabecular bone marrow (B-Bi), perivascularly in the marrow space (arrow head; Bii), in trabecular bone (C), and below the growth plate (D). (Di) No staining was found in the growth plate. (E-F) Confocal microscopy revealed tdTomato+ signal in 12-week old mice along the trabecular bone (E) and in trabecular bone marrow (Ei-ii). (Ei-ii) tdTomato+ was found to be perivascular in the marrow space (arrow head). (F) No staining was found in the growth plate. Additionally, tdTomato+ is expressed on the bone surface (yellow arrow) and embedded within bone (green arrow) in 12-week old mice. n=4. Scale bar 50µm unless otherwise indicated.
Figure 2: tdTomato+ bone marrow cells appear around sinusoids and contribute to osteoblast and osteocyte populations over time in cortical bone. To assess whether LepR-cre was actively expressed in adult tibia, limbs were harvested from 8- and 12-week-old mice. Lepr-cre;tdTomato mice and processed for histological analyses with the nuclear dye DAPI. (A) tdTomato+ signal was found on the endosteal surface of cortical bone at 8-weeks. (B-D) Representative image of a 12-week old tibia. (Ci-ii) Confocal microscopy revealed LepR signal perivascularly in the marrow space (Ci) and along the cortical bone surface (Cii). (D) LepR is expressed on the bone surface.
(yellow arrow) and embedded within bone (green arrow). n=4. Scale bar 50µm. (E) Flow cytometry analyses revealed that in 12-week-old mice tdTomato⁺ make up 1.23-7.65% and 1.35-6.36% of bone marrow cells in the tibia and femur, respectively. (F) Exclusion of CD45/Ter119⁺ cells reveals 0.07-0.35% and 0.09-0.34% tdTomato⁺ cells in the tibia and femur, respectively. n=3, Values are percentages +/- SD.

Figure 3: Axial tibia loading of 12-week-old Lepr-cre;tdTomato mice. (A) Schematic of the experimental plan and tibia loading set up. (B) The right tibia of 12 week old mice was axially loaded at 11N for 40 cycles with 10 sec rest periods per day for a total of 14 days. The left tibia
were not loaded and used as non-loaded internal controls. (C) Schematic representation of analyses done on tibia. Whole bone microCT was performed and cortical bone analysed between 15 and 90% of the total tibial length, confocal microscopy on cryosections and dynamic histomorphometry were performed on cross-section located between 45-50% of the tibial length. (D) Whole bone analyses of cortical bone between 15-85% of the total tibial length, excluding proximal and distal methaphyseal bone showing cross sectional area and ellipticity. Loaded: red, static: black, line graph represent means +/-SEM, n=7. Statistical significance of differences along the entire tibial shaft is represented as a heat map, red p< 0.001, yellow 0.001≤p<0.01, green 0.01≤p<0.05 and blue p≥0.05. (E-F) Dynamic histomorphometry analysis of tibia transverse section reveals tibial compressive loading enhances endosteal and periosteal cortical bone formation. Relative mineralizing surface over bone surface, mineral apposition rate, and bone formation rate at the endosteal (E) and periosteal (F) surface of mechanically loaded tibia. n=5. Mean +/-SD.
Figure 4: Tibial compressive loading doesn’t alter proliferation nor location of Lepr-cre:tdTomato cells. (A-B) Flow cytometry analyses of bone marrow cells following mechanical loading of Lepr-cre:tdTomato mouse tibia. (A) Flow cytometry analyses revealed loading did not alter the percentage of tdTomato+ cells. (B) Exclusion of CD45+ and Ter119+ cells reveals a trend towards an increase in tdTomato+ cells following tibia loading, n=4. (C-D) Tibial compressive loading doesn’t alter the location of tdTomato+ cells. (C) Representative image of tibia transection, scale bar 100µm. (D) The percentage of tdTomato+ cells on the endosteal or periosteal surface and embedded with the bone was not altered in cortical bone following tibia compressive loading. n=7 (E) Analysis of the location of bone formation along the surface of the endosteum, upper graph: average number of label observed by dynamic histomorphometry (n=4), lower graph: average number of tdTomato+ cells observed lining endosteum surface on confocal images (n=3). Statistical tests employed unpaired two tailed student t-test. Mean +/- SD *P<0.05
Figure 5: Phenotypic analysis of Lepr-cre;tdTomato and Lepr-cre;tdTomato;AC6<sup>fl/fl</sup> mice at 8 and 12 weeks. (A) Photographs of Lepr-cre;tdTomato and Lepr-cre;tdTomato;AC6<sup>fl/fl</sup> mice at 12 weeks old. (B) Full body µCT scans comparing the two genotypes. (C) Gel electrophoresis of genotyping showing a band at 260bp for AC6 floxed gene. (D) Cortical bone midshaft geometry of 12 weeks old of Lepr-cre;tdTomato and Lepr-cre;tdTomato;AC6<sup>fl/fl</sup> mice.
Figure 6: Axial tibia loading of 12-week-old Lepr-cre;tdTomato;AC6<sup>fl/fl</sup> mice. (A) Whole bone analyses of cortical bone of mice lacking AC6 between 15-85% of the total tibial length, excluding proximal and distal methaphyseal bone showing cross sectional area and ellipticity. Loaded: red, static: black, line graph represent means +/-SEM, n=6. Statistical significance of differences along the entire tibial shaft is represented as a heat map, red p< 0.001, yellow 0.001≤p<0.01, green 0.01≤p<0.05 and blue p≥0.05. (B-C) Mice lacking AC6 demonstrated poor mineralization on the endosteal surface, indicated by a lack of labelling at the endosteal surface in both loaded and non-
loaded tibia. (B) Relative mineralizing surface over bone surface, mineral apposition rate and bone formation rate at the endosteal surface of mechanically loaded tibia. (C) Relative mineralizing surface over bone surface, mineral apposition rate and bone formation rate at the periosteal surface. n=5 for Lepr-cre;tdTomato. n=3 for Lepr-cre;tdTomato;AC60/61. Mean +/- SD.
A

Control

Loaded

B

Endosteum

Periosteum

Osteocytes

C

Average number of label

Length of endosteum (%)

Presence of tdTomato^+ cell

Length of endosteum (%)

741
Figure 7: Tibial compressive loading doesn’t alter proliferation nor location of Lepr-cre;tdTomato cells in Lepr-cre;tdTomato and Lepr-cre;tdTomato;AC6<sup>0/0</sup> mice. (A) Representative image of tibia transection of Lepr-cre;tdTomato;AC6<sup>0/0</sup> mice following tibia compressive loading, scale bar 100µm. (B) The percentage of tdTomato<sup>+</sup> cells on the endosteal, periosteal surface and embedded with the bone was not altered in cortical bone. n=4. Statistical tests employed unpaired two tailed student t-test with Wilcoxon correction. Mean +/- SD. (C) Analysis of the location of bone formation along the surface of the endosteum, upper graph: average number of label observed by dynamic histomorphometry (n=4), lower graph: average number of tdTomato<sup>+</sup> cells observed lining endosteum surface on confocal images (n=3). Statistical tests employed unpaired two tailed student t-test. Mean +/- SD *P<0.05