Single Cell Cortical Bone Transcriptomics Defines Novel Osteolineage Gene Sets Altered in Chronic Kidney Disease

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Abstract

The bone dysfunction caused by chronic kidney disease (CKD) dramatically increases fracture risk, however, the affected cell types which lead to skeletal disease in CKD remain largely unknown. To this end, flow cytometry and scRNAseq were performed on long bone cells from Sost-cre/Ai9 mice, and pure osteolineage transcriptomes were identified, including novel osteocyte-specific gene sets. Clustering analysis isolated osteoblast precursors that expressed *Tnc*, *Mmp13,* and *Spp1,* and a mature osteoblast population defined by *Smpd3*, *Col1a1*, and *Col11a1*. Osteocytes were demarcated by *Cd109*, *Ptprz1, Ramp1, Bambi, Adamts14*, *Spns2, Bmp2*, *Wasl,* and *Phex*. We validated our *in vivo* scRNAseq using integrative *in vitro* promoter occupancy coupled with transcriptomic analyses of a conditional, temporally differentiated MSC cell line. Further, trajectory analyses predicted osteoblast-to-osteocyte transitions via defined pathways associated with a distinct metabolic shift. Using the adenine mouse model of CKD, at a time point prior to major skeletal alterations, gene expression in all stages of the osteolineage was markedly disturbed. In sum, we defined distinct populations of osteoblasts/osteocytes at the single cell level. Using this roadmap of gene assembly, we demonstrated unrealized molecular defects across multiple bone cell populations during CKD, suggesting an earlier and more broad bone pathology than previously recognized.

Significance Statement

Bone loss leading to fracture is a critical consequence of CKD, thus understanding the cellular dynamics controlling bone formation and function is necessary for developing new therapeutic approaches. We leveraged flow cytometry and scRNAseq from Sost-cre/Ai9 mice to identify cortical bone osteoblast precursor, mature osteoblast and osteocyte transcriptomes. Novel osteolineage genes were validated in cortical bone and using *in vitro* promoter occupancy and transcriptomic analyses. Single-cell flux estimation analysis (scFEA) showed metabolic heterogeneity between osteoblast precursors and osteoblasts/osteocytes. Using a CKD mouse model, gene alterations were found in cells at all stages of the osteolineage, suggesting a simultaneous and wider effect of CKD on bone than previously understood. Thus, our studies underscore the concept that targeting the activity of multiple bone cell types and differentiation stages is likely necessary to improve the musculoskeletal disease associated with CKD.

Introduction

Osteocytes are derived from osteoblasts through a dynamic and spatio-temporal process regulated within cortical bone [1]. The exposure of these cells to the bloodstream through dendrites allows osteocytes to play key endocrine functions, including sending and receiving signals to vascularized organs such as the kidney. A complete identification of the osteocyte and osteocyte precursor transcriptomes is critically needed to understand the molecular pathways of osteolineage differentiation as well as the contribution of novel osteoblast/osteocyte genes to musculoskeletal disease.

Common bone pathologies are associated with osteocyte dysfunction, including aging [2], osteoporosis [3], and chronic kidney disease (CKD) [4]. CKD is a worldwide public health problem with an estimated 5-10 million lives lost each year [5]. The manifestation of CKD is associated with bone loss and abnormal changes of hormones including reduced 1,25$(OH)_2$ vitamin D (1,25D), coupled with elevated parathyroid hormone (PTH) and fibroblast growth factor (FGF23) [6]. Fracture is the most important clinical outcome of the bone disorder that occurs in CKD. The CKD patient hip and spine fracture rates range between 2- to 4- fold greater than the general population [7]. Although fractures are more common and deadly in CKD patients, the dynamic and spatial contribution of osteolineage cells in bone loss as well as the molecular mechanisms and spatial transcriptional reprogramming that contributes to bone loss in CKD remains to be determined.

Herein, we developed a successful workflow to enrich cortical bone osteoblast and osteocyte cell populations using flow cytometry followed by scRNAseq. Our transcriptomic data identified multiple osteoblast populations, as well as novel osteocyte-specific genes, and revealed cell-specific metabolic profiles. We identified previously unrecognized transcriptional reprogramming prior to major bone ultrastructural changes in a CKD mouse model, suggesting that therapeutics for this common bone dysplasia mostly likely not be exclusive for one cell type.

Results

Mouse osteoblast/osteocyte transcriptomic profiling at single cell resolution

The osteocyte transcriptomic profiling at the single cell level solely from long bones remains uncharacterized. To enrich our cell sample preparation, we used Sclerostin (Sost)-cre/Ai9 'Tomato' reporter mice to isolate fluorescently-labeled osteoblasts/osteocytes at 10 weeks of age. Consistent with previous characterization [8], SOST-cre/Ai9 ('tdTomato' reporter) mice had some basal Cre activation in osteocytes as evidenced with the presence of red fluorescence in mouse tail vertebrae (**Figure 1A**). Following cortical bone digestion using collagenase/EDTA, the cells were sorted, and the Ai9/tdTomato$^+$ fraction represented approximately 1.5% of total cells (**Figure 1B**). As determined by qPCR, the Ai9/tdTomato$^+$ cells were highly enriched for osteocyte marker mRNAs *Fgf23* (40-fold), *Phex* (102-fold), *Dmp1* (172-fold), and *Pdpn* (12-fold) compared to the Ai9/tdTomato$^-$ population (**Figure 1B**).

To isolate the transcriptome of the Ai9/tdTomato$^+$ population, we performed scRNAseq. Approximately 1,200 cells were successfully recovered after sequencing with an estimation of 130,000 reads per cell and 97% valid barcodes. Further stringent bioinformatic analyses were performed to exclude low-quality cells; for downstream analysis, we retained only cells that had less than 3500 genes to exclude doublets, and less than 15% of mitochondrial genes to exclude potential dead cells. To aggregate cells based on their similarities, principal component analysis (PCA) was performed on highly variable genes and the result was used as input for clustering using Louvain algorithm with multilevel refinement and Uniform Manifold Approximation and Projection (UMAP) for dimension reduction (**Figure 1C**). To identify gene specific markers in each cluster, we used the function FindMarkersAll from the MAST method algorithm. The quality of clustering was assessed by the dotplot of top marker genes obtained from individual cluster (**Figure 1D**).

The transcriptomic profiling of Ai9/tdTomato^{+} cortical bone cells identified a total of six cell populations, including two osteoblast clusters and one osteocyte cluster (**Figures 1C and 1D**). Marker analysis revealed that within the osteoblast population, one cell type was characterized by higher expression of *Smpd3*, *Bglap, Col1a1*, and *Col11a1* mRNAs. The second, referred to as "Tnc/Mmp13 osteoblast," was defined by a high expression of *Tnc*, *Mmp13, Serping1 and Spp1*, which was consistent with previous subpopulation analyses [9]. Osteocytes were associated with a cluster showing the highest expression of *Phex* and *Dmp1*. Other genes that defined osteocytes were *Cd109*, *Dkk1*, and *Ptprz1* (**Figure 1D**). Our analyses also identified two distinct populations of hematopoietic cells. The first population annotated "Hematopoietic I" showed high expression of *Cybb*, *Chil3*, and *Ltf* whereas the "Hematopoietic II" cells were characterized by high expression of *Clec4d*, *Il1r2*, and *Cxcl2*. Bone marrow derived endothelial cells ('BMEC') were also identified and distinctly defined by *Cdh5*, *Plvap*, and *Ptprb* gene transcripts (**Figure 1D**). As expected, *Col1a1* was identified only in osteolineage cells (**Figure 1E**), underscoring the ability to identify transcripts unique to cortical bone cells.

Our UMAP clustering confirmed that the Tnc/Mmp13 osteoblast population clustered farther from osteocytes when compared to the dimensional separation between the defined more mature osteoblasts (high *Bglap* expression (**Figure 1E**)) and osteocytes (high *Phex* expression (**Figure 1E**)). These data suggest that the Tnc-Mmp13 osteoblasts represent a precursor osteoblast population. Importantly, we isolated 25-highly and preferentially expressed genes in osteocytes. Among the genes which were not previously identified as osteocyte-specific based on the recent proposed bulk RNAseq-based osteocyte transcriptome [10] were *Ramp1, Ptprz1, Ptgis1, Plpp1, Pdgfa, Cd109, Bmp4, Bambi, Wasl, Spns2, Myo1b, Gm41724, Ccn4, Ccdc194, Car12, Bmp2,* and *Adamts14*. The comparison of recent osteocyte transcriptomes highlights the common (*Dkk1*, *Dmp1*, *Irx5, Col24a1, Ackr3*) (**Figure 1F**). The polar plot in **Figure 1F** highlighted transcripts

identified from our dataset (scRNAseq on long bone), Wang and colleagues (scRNAseq on long bone and calvaria) [9] and Youlten and colleagues (bulk RNAseq on long bone) [10] (**Figure 1F**).

To further test whether the genes identified as highly expressed in osteolineage cells in our scRNAseq analyses were not derived from bone marrow cells, we compared the mRNA expression of these genes in mouse cortical long bone (osteoblast/osteocyte-enriched fraction) *versus* bone marrow. In this regard, *Mmp13*, *Cthrc1*, *Smpd3*, *Ptprz1*, and *Cd109* were highly expressed in cortical bone suggesting that the identified genes were preferentially expressed in osteolineage cells (**Figure 1G**). *Epor* expression tested as a control was not increased in cortical bone when compared to bone marrow expression levels, whereas defined osteocyte genes *Phex, Pdpn, Dmp1, Fgf23,* and *Sost* were all increased (**Figure 1G**). To determine the cellular differentiation patterns that govern the maturation of osteoblasts to osteocytes, we performed pseudotime analysis. These analyses confirmed that the osteocyte cluster of cells identified from our dataset derived from the osteoblast subset and identified the Tnc/Mmp13 osteoblast as a precursor population (**Figure 1H**).

scRNAseq identifies signaling pathways involved in osteoblast transition to osteocyte

To identify the molecular pathways involved in the transition from osteoblast to osteocyte at single cell resolution, we analyzed differentially expressed osteoblast/osteocyte genes using the Ingenuity Pathway Analysis (IPA). Further, a comparison analysis was performed to identify signaling pathways in osteoblasts *versus* osteocytes. We found an enrichment of "*GP6 Signaling*", a major signaling receptor for collagen in osteoblasts, which was almost completely shut down in osteocytes (**Figure 2A**). In contrast, the "*Axonal guidance*", the "*Differentiation via BMP receptors*", "*TGFβ signaling*" and the "*Iron homeostasis signaling*" pathways that were not highly enriched in osteoblasts were significantly increased in osteocytes (**Figure 2A**). Among the genes

predicted to drive "*Axonal guidance*" were *Adamts14*, *Bmp2*, *Bmp4*, and *Wasl*. Furthermore, IPA analysis predicted EGFR among the top upstream regulators of osteoblastic pathways whereas FGF2 was predicted to be one of the primary upstream regulators that identified with the osteocyte maturation pathway (**Figure S1A**). Further, our in-silico analysis identified an enriched cell activation in osteoblasts, associated with genes such as *Col11a1*, *Col11a2*, and *Col1a1* which were significantly attenuated in the osteocytes (**Figure 2A**). Overall, these data suggest that osteoblasts and osteocytes are defined by unique pathways that are associated with their individual homeostatic functions.

To predict the transcriptional profiles of osteocyte genes across osteolineage cells, we used pseudotime analysis to track the computational-derived kinetics of gene expression during differentiation. We found that "pan-osteolineage" markers *Col1a1*, *Col1a2* and *Runx2* showed a relatively stable expression during osteoblast to osteocyte differentiation (**Figure 2B**). In contrast, *Mmp13, Tnc,* and *Spp1* pseudotemporal progression predicted a decrease during differentiation from Tnc/Mmp13 osteoblasts to osteocytes (**Figure 2C**). Further, *Bglap, Col11a2,* and *Smpd3* expression increased from the Tnc/Mmp13 precursor osteoblasts to osteoblasts, but decreased when the osteoblast population transitioned to osteocytes (**Figure 2D**). In osteocytes, the kinetic profiling of *Dmp1, Irx5, Ackr3, Phex, Ptprz1,* and *Cd109* showed progressive positive regulation with differentiation (**Figure 2E**). These data confirmed the dynamic differentiation of canonical genes during the transcriptional reprogramming required for osteoblast transition to osteocytes, as well as identified new genes associated with cortical bone osteolineage.

To distinguish the metabolic heterogeneity between osteoblasts and osteocytes, we applied the recently developed computational method single-cell flux estimation analysis (scFEA) [11] that uses a systematically reconstructed human metabolic map to infer the cell-wise cascade from the transcriptome to metabolome. This approach applies multilayer neural networks to capitulate the nonlinear dependency between enzymatic gene expression and reaction rate fluxome from

scRNAseq datasets. By reconducting the cell clustering analysis using the original UMAP labeling (see **Figure 1C**), we identified metabolic fluxes in Tnc/Mmp13 osteoblasts, osteoblasts and osteocytes (**Figure S1B**) and found a decrease of glycolytic, TCA, and fatty acid metabolic reactions when pre-osteoblasts transition to osteoblasts/osteocytes (**Figure S1C**). Specifically, the genes controlling successive glycolytic reactions from glucose to pyruvate pathways were decreased with transition of Tnc/Mmp13 osteoblasts to osteoblasts (**Figure 2F** and **Figure S1D**). Further, genes associated with the conversion of fatty acid to acetyl-CoA (**Figure 2F** and **Figure S2E**) and the glutamate export also decreased with cell maturation (**Figure S2F**). Importantly, whereas the conversion of serine to cysteine decreased with osteoblast differentiation, the transformation of cysteine to pyruvate increased when Tnc/Mmp13 osteoblasts transitioned to osteoblasts/osteocytes, a potential metabolic route to supply cells with pyruvate since the glycolytic pathway is down regulated during osteoblast differentiation (**Figure 2G**). Based on the scRNAseq dataset, the top metabolites in osteolineage cells were the inosine monophosphate (IMP), succinyl coenzyme A, and pyrimidine in pre-osteoblasts; the farnesyl pyrophosphate (FPP), Cytidine-5'-diphosphate (CDP), and malate in osteoblasts; and the xanthosine monophosphate (XMP), acetyl CoA oxaloacetate, and malate in osteocytes (**Figure 2H**). Collectively, the transcriptional profile across cortical bone cell types predicted differential metabolic states in the osteoblast cell population subsets and within osteocytes.

Identification of genes at staged differentiation associated with developmental processes

To validate the osteoblast/osteocyte genes identified from our *in vivo* scRNAseq experiment, the mRNA expression of these genes was tested in mesenchymal progenitor cell (MPC)-2 cells *in vitro*. MPC2 cells were recently characterized as harboring the ability to derive osteoblast- and osteocyte-like cells when cultured in osteogenic media [12]. After 1-4 weeks of culture, the

differentiated cells showed increased alizarin red staining which reflected the increase in mineralization of the differentiated cells [12]. Our molecular analyses demonstrated that mRNAs encoding *Col1a1* and *Sost* increased with cell differentiation with the highest level observed at 4 weeks (**Figure 3A**). Importantly, the expression of *Ptprz1* and *Sost* were only detected at 3 and 4 weeks of osteocyte differentiation confirming our finding of *Ptprz1* as a likely late osteoblast/osteocyte gene.

To identify the molecular events associated with osteolineage differentiation, we next employed a comprehensive genomic and transcriptomic analyses using RNAseq and ATACseq on MPC-2 cells [13]. Based on the kinetic profile performed in **Figure 3A**, a time point of 3 weeks of MSC to osteocyte-like cell differentiation was chosen for RNAseq and ATACseq to capture differentially regulated genes in osteoblasts and osteocytes. Our unbiased approach identified several genes with increased chromatin accessibility and/or gene expression during MPC2 differentiation including osteocalcin (*Bglap*), osteopontin *(Spp1), Col11a1,* and *Col11a2* (**Figure 3B and Figure S2A-F**). By performing integrative and correlative analyses of the ATACseq and RNAseq, we confirmed our observed changes in mRNA expression and chromatin accessibility in the ATAC-seq dataset. Using this approach, we identified 150 genes with significantly more open chromatin status leading to higher gene expression levels after differentiation (**Figure 3C**), whereas 44 genes were downregulated with notably less DNA accessibility (**Figure 3C**).

The upregulated genes identified from differential expression analysis associated with changes in chromatin accessibility (**Figure 3D**) were then subdivided by gene ontology (GO). Among the GO terms that were increased during osteoblast/osteocyte differentiation were functions related to bone mineralization as well as cellular morphology changes including membrane branching (**Figure 3E**). For example, and as expected, the chromatin accessibility at the osteocalcin (Bglap) promoter region was also increased with differentiation. Further, increased chromatin accessibilities within the promoter regions of *Col8a1*, *Mgp*, *Igfbp5*, *Sema3a* and *Tnc* genes were

also observed with cell maturation (**Figure 3F**). Interestingly, these genomic changes detected during the cell transitions were robustly and positively associated with their corresponding gene expression levels (**Figure 3G**).

We next tested the chromatin accessibility at the genomic regions of a set of osteolineage genes identified in the scRNAseq. For instance, among the Tnc/Mmp13 osteoblast signature genes, we detected increased chromatin accessibility at the *Mmp13*, *Serpine2,* and *Lifr* promoter regions in differentiated cells versus MSC control (**Figure S3A-C**). We also observed high chromatin accessibility at the promoters of the *Serpinf1* and *Cthrc1* genes (**Figure S3D-E**), that were defined as expressed by fully differentiated osteoblasts based upon our *in vivo* scRNAseq data. Regarding osteocyte genes, we observed an increase chromatin accessibility at *Ackr3, Cd109, Ptgis, Spns2,* and *Bmp2* promoter regions (**Figure S3F-G** and **Figure S4**). Importantly, non-canonical osteocyte genes identified from our scRNAseq analysis including *Ccn4, Adamts14, Spns2,* and *Bmp2* were significantly upregulated in osteocyte-like cells when compared to undifferentiated cells (**Figure 3H**). *Ptgis* identified in our dataset and Wang et al dataset [9] was also significantly increased with differentiation. *Col24a1* found in our dataset and Youlten et al dataset [10] was also increased (**Figure 3H**). Taken together, these results pinpoint genomic regions of interest associated with osteoblast differentiation that may play critical roles in cellular transcriptional reprogramming and during cell differentiation.

Impairment of osteoblast/osteocyte genes prior to cortical bone deterioration in CKD.

We next assessed the dynamic transcriptional profile of identified osteoblast and osteocyte genes within cortical bone prior to the development of cortical porosity in CKD, a severe outcome that leads to bone fracture. We used a mouse model where CKD can be induced by providing an adenine-containing diet which leads to a progressive loss of kidney function [14]. This model

reflects the phenotype observed in humans that is characterized by progressive tubular atrophy, immune cell infiltration, and fibrosis [14]. With a focus on testing osteoblast/osteocyte gene regulation in cortical bone at a CKD onset prior to major ultrastructural changes in bone, cohorts of C57BL/6 mice were placed on control diet or a 0.2% adenine–containing diet for 2 or 4 weeks. At this stage of the disease (2 weeks), serum phosphate, alkaline phosphatase, and calcium were not significantly changed compared to controls (**Table 1**). Blood urea nitrogen (BUN) was monitored for declines in renal function, and as expected, the adenine diet was associated with significantly increased BUN (**Table 1**). The cortical porosity and bone volume remained unchanged at 2 or 4 weeks in male or female CKD mice (**Figure 4C**). Serum bioactive iFGF23 concentrations were markedly elevated in mice with CKD, which was associated with significant cortical bone *Fgf23* mRNA increases at 4 weeks (**Figure 4D-E**).

We next determined the effects of CKD on highly expressed osteoblast and osteocyte genes. During CKD, *Mmp13*, identified in the osteoblast precursor population, was increased at 4 weeks (**Figure 4F**). In contrast, precursor osteoblast genes such as *Tnc, Gdpd2, Serping1,* and *Igfbp5* were decreased during CKD progression. The expression of the osteolineage gene *Col1a1*, as well as osteoblast-specific genes *Bglap, Cthrc1, Smpd3* and osteoblast/osteocyte marker *Dmp1*, were strongly impaired in the mice with CKD (**Figure 4G**). Additionally, osteocyte genes including *Sost*, *Pdpn, Phex, Ptprz1* and *Adamts14* were dramatically downregulated early in CKD (**Figure 4H**). These unexpected findings support that the changes in bone that likely lead to the severe CKD musculoskeletal phenotypes occur rapidly and dramatically across multiple cortical bone cell populations, with cell-specific and time-dependent misregulation of osteoblast lineage genes prior to major bone structural deformation.

Discussion

To address the bone fracture epidemic in CKD patients [15, 16], there is a need to understand bone-forming cell heterogeneity as well as isolate key gene networks with potential impact on bone homeostasis. Our cortical bone single cell analysis identified two osteoblast cell populations as well as a distinct osteocyte cluster. The genes demarcating each cell type were confirmed as highly enriched in cortical bone as well as being upregulated during osteoblast differentiation *in vitro*. Interestingly and unexpectedly, at early CKD onset in mice, there was a dramatic misregulation of gene expression in the three cortical bone cell types prior to major bone ultrastructural changes.

Recent studies using bulk RNA sequencing proposed an osteocyte transcriptome which was comprised of 28 genes [10]. While we observed some overlap of genes within the proposed transcriptome, our scRNAseq analysis identified additional genes which we showed were highly enriched in osteocytes (see **Figure 1F**). We also observed some overlap when comparing our osteocyte gene sets with those from studies performed by Wang et al [9] and Youlten et al [10]. It is likely that some differences of osteocyte gene profiling observed between our studies and those of others are due to the fact that we exclusively used long bones for cell isolation whereas other studies have sequenced a mix of long bone and calvariae, or used bulk total cortical bone sequencing [9, 10]. Future studies may be needed to continue to sub-set these gene profiles and expand cell-specific targets as more datasets become publicly available.

Our bone scRNAseq bioinformatic analyses identified a population of Tnc/Mmp13 mRNA-containing osteoblasts as precursors of a mature osteoblast population of cells. Mmp13, the most expressed gene in this cell type has been described as a direct target of osteoblast-specific transcription factor osterix (Sp7) in osteoblasts [17] and known to be activated by Runx2, the master transcription factor for osteoblastogenesis [18]. A recent study defined the molecular mechanisms driven by Sp7 to control osteocyte dendrite formation [9]. Whether directly targeting

Mmp13 may influence osteoblast differentiation and osteocyte maturation remains to be investigated. CKD has been associated with intrinsic impairment in osteoblast and osteocyte maturation [19]. Thus, we identified osteolineage genes that potentially play roles in the pathogenesis of CKD-mediated osteoblast differentiation and during osteocyte maturation failure.

Another primary goal of this work was to decipher the osteolineage gene regulation during CKD onset. We established a critical link between both osteoblast at early and mature stages, as well as early osteocyte genes that were suppressed prior to the development of CKD major bone ultrastructural changes. These studies imply that targeting one bone cell type in CKD bone disease will likely not be fully effective since damage may be done in early precursor cells, with these cells either having faulty differentiation or carrying these gene changes through differentiation where they may impact mature cells. We also found a decrease in cortical bone Sclerostin expression at an early stage of CKD in mice (**Figure 4H**). Several possibilities could explain the rapid shutdown of this key osteocyte gene transcription at the CKD onset. In a paracrine signaling manner, rapid decreases of osteocyte genes *Sost* and likely *Dkk1* may represent an adaptive mechanism to maintain effective Wnt signaling, osteoblast differentiation and an attempt to delay the initial development of renal osteodystrophy.

The skeleton is known as an important regulator of systemic glucose homeostasis, with osteocalcin and insulin thought to represent the prime mediators of the interplay between bone and energy metabolism [20, 21]. Using the recently developed computational tool single-cell flux estimation analysis (scFEA) [11] that calculates the cell state metabolomic in scRNAseq datasets, our data predicted the *in vivo* metabolomic transition during osteoblast differentiation. Our analysis identified the highest glycolysis and glutamine metabolism states in osteoblast precursors (**Figure 2F** and **Figure S1F**). The conversion of arginine to ornithine is similar across all the osteolineage cells (**Figure S1G**). Other metabolomic pathways, including the conversion of citrulline/aspartate to arginosuccinate or acetyl glucosamine to hyaluronic acid are conserved

regardless of cell differentiation or cell types (**Figure S1G**). It will be interesting in future studies to build on these finding to provide genetic evidence that some osteoblast precursor genes identified may be critical in supporting osteoblast differentiation as well as influencing global energy metabolism.

In summary, combining genomic, transcriptomic, and predictive metabolic profiling approaches, our studies identified osteolineage genes associated with distinct cell populations of osteoblast precursors, mature osteoblasts and osteocytes. Genes within these three cortical bone cell populations are misregulated in CKD prior to the development of cortical porosity. Our findings support that CKD osteoblastogenesis is likely impaired prior to the increase of osteoclast activity; thus, it will be necessary to determine the contribution of the newly identified osteolineage genes in CKD-induced bone loss as well as other common musculoskeletal diseases.

Methods

Sost-CreERT2-Cre+/Ai9 mice: Animal protocols and studies were approved by the Indiana University Institutional Animal Care Committee and conform to the NIH guidelines [22]. Male and female Sost-CreERT2-Cre+ mice were crossed with the Ai9 mouse in which the recombination event causes activation of tdTomato fluorescent protein to generate Sost-CreERT2 Cre+/Ai9 [8]. The Cre- were used as negative control. Both males and females were included in this study. Eight weeks mice were sacrificed, and long bones (femurs, tibiae, and humeri) were collected, pooled followed with a sequential bone digestion (see below).

Preparation of mouse long bones for osteoblasts/osteocytes isolation: Isolated long bones were placed in 100 mm petri dishes containing αMEM with 10% penicillin and streptomycin. Any remaining muscle and connective tissue from the bones were removed and the periosteum was scraped away using a scalpel. Long bones were then washed, the bone epiphyses cut, and the marrow flushed using a 27G syringe. Further, the bones were cut in half lengthwise and then into 1 to 2 mm lengths using a scalpel and briefly washed with Hank's Balanced Salt Solution (HBSS; Hyclone).

Bone digestion and isolation of osteoblasts and osteocytes: Long bone pieces were digested as described previously [23]. In brief, bones were immerged in warmed collagenase type IA (2 mg/mL; Sigma) and EDTA alternately and incubate at 37°C for 25 min on a circular shaker (~200 rpm). Bone extracted cells were then centrifuged at 600 rpm for 15 minutes at 4°C, washed 3 times and the pellet resuspended in αMEM supplemented with 10% FBS. TdTomato^{+} cells were then sorted using Fluorescence-activated cell sorting (FACS) Aria Fusion (BD Biosciences). TdTomato^{-} cells were used as negative control for the sorting procedure.

CKD mouse models: Male and female C57BL/6J mice ware purchased from the Jackson Laboratory and housed in the Indiana University School of Medicine Laboratory Animal Resource Center (LARC) for at least 1 week for optimal acclimatization prior to the start of the experiments

and according to previous protocols [24]. The adenine diet model was used to induce chronic kidney disease (CKD) in male and female mice. At 8 weeks of age, mice were fed with a control casein-based diet (0.9% phosphate and 0.6% calcium, TD.150303 Envigo), or CKD-causing diet containing 0.2% adenine (TD.160020; Envigo) for 2 or 4 weeks. Diets and water were provided ad libitum.

Micro-computed tomography (µCT): Paraformaldehyde fixed femora from CKD and healthy mice were scanned, reconstructed, and analyzed as previously described [25]. Briefly, femurs were scanned at 10-µm resolution, 55-kV peak tube potential and 8W. Standard output parameters related to cortical bone mass, geometry, and architecture were measured and reported [26].

Single cell library preparation: We applied single cell master mix with lysis buffer and reverse transcription reagents following the Chromium Single Cell 3' Reagent Kits V3 User Guide, CG000183 Rev A (10X Genomics, Inc.). This was followed with cDNA synthesis and library preparation according to standard methods. All libraries were sequenced in Illumina NovaSeq6000 platform in paired-end mode (28bp + 91bp).

Data processing/bioinformatic analyses: The 10x Genomics Cellranger (v. 6.0.0) pipeline was used to demultiplex raw base call files to FASTQ files and reads aligned to the mm10 murine genome using STAR [27]. Cellranger computational output was then analyzed in R (v 4.0.2) using the Seurat package v. 4.1.0 4 [28]. Seurat objects were created, and the top principal components were used to perform unsupervised clustering analysis and visualized using UMAP dimensionality reduction. Using the Seurat package, annotation and grouping of clusters by cell type was performed manually by inspection of differentially expressed genes using MAST method [29] for each cluster, based on canonical marker genes in the literature. The selected markers were visualized on UMAP coordinate as gene expression density using R package Nebulosa [30]. To

perform the pseudotime analysis on integrated Seurat object, cells were divided into individual gene expression data files organized by previously defined cell type. R package Monocle v3 [31] was used for dataset analysis. Outputs were obtained detailing the pseudotime cell distributions for each cell type. Positional information for the monocle plot was used to subset and color cells for downstream analyses [31]. Ingenuity Pathway Analysis (IPA) was used to predict the statistically significant canonical pathways upregulated in osteoblasts and osteocytes.

scFEA: The python package v1.2 of single cell flux estimation analysis (scFEA) was applied to estimate cell-wise metabolic flux rate against the whole human metabolic map by using the scRNA-seq data [11]. Default parameters were utilized. Statistical significance of the differences in metabolic flux between cell groups was assessed by Mann Whitney test.

Culture of the MPC cell line: Murine progenitor cells clone 2 (MPC2) [12], a conditionally immortalized mesenchymal stem cell line, were cultured in αMEM (Invitrogen, Thermo-Fisher Scientific) supplemented with 10% fetal bovine serum (FBS; Hyclone), 25 mM L-glutamine, and 25 mM penicillin-streptomycin (Sigma-Aldrich, St. Louis, MO, USA) at 33°C and 5% CO2 to proliferate. Cells were plated at a density of 1.0×10^5 cells per well in 6-well plates and incubated overnight before being transferred to a 37°C incubator for osteogenic differentiation and cultured in maintenance media supplemented with mineralization conditions of 4 mM beta-glycerophosphate and 50 μg/mL ascorbic acid. Cells were differentiated for 0-4 weeks where indicated, with osteogenic media changes every 2-3 days.

Bulk mRNA sequencing: MPC2 cells were differentiated for 3 weeks in osteogenic media or plated in an undifferentiated state at 33°C (see cell culture methods above). Total RNA was extracted (with a DNase step) using the same methods as described in “RNA preparation” section of methods. Total RNA was evaluated for its quantity and quality using Agilent Bioanalyzer 2100. The RNA Integrity Number (RIN) for all of the samples was 10 or higher. 100 ng of total RNA was

used. cDNA library preparation includes mRNA purification/enrichment, RNA fragmentation, cDNA synthesis, ligation of index adaptors, and amplification, following the KAPA mRNA Hyper Prep Kit Technical Data Sheet, KR1352 – v4.17 (Roche Corporate). Each resulting indexed library was quantified and its quality accessed by Qubit and Agilent Bioanalyzer, and multiple libraries pooled in equal molarity. The pooled libraries were denatured and neutralized before loading to NovaSeq 6000 sequencer at 300 pM final concentration for 100b paired-end sequencing (Illumina, Inc.). Approximately 30-40M reads per library were generated. A Phred quality score (Q score) was used to measure the quality of sequencing. More than 90% of the sequencing reads reached Q30 (99.9% base call accuracy). The sequencing data were first assessed using FastQC (Babraham Bioinformatics, Cambridge, UK) for quality control. The reads were mapped to the mouse genome mm10 using STAR (v2.7.2a) [27]. RNAseq aligner with the following parameter: "--outSAMmapqUnique 60" Uniquely mapped sequencing reads were assigned to Gencode M22 gene using featureCounts (v1.6.2) [32] with the following parameters: "–p –Q 10 -O". The genes were kept for further analysis if their read counts > 10 in at least 3 of the samples, followed by the normalization using TMM (trimmed mean of M values) method and subjected to differential expression analysis using edgeR (v3.24.3) [33]. Gene Ontology and KEGG pathway functional enrichment analysis was performed on selected gene sets, e.g., genes undergoing both significantly differential expressions and notable changes of open chromatin accessibilities, with the cut-off of false discovery rate (FDR) < 0.05 using DAVID [34]. Canonical pathways from RNAseq data were generated through the use of IPA (QIAGEN Inc., https://www.qiagenbioinformatics.com/products/ingenuity-pathway-analysis) [35]. N=3 samples per condition.

Assay for Transposase-Accessible Chromatin sequencing (ATACseq): Cells used for ATACseq were plated, differentiated, and treated identical to samples for RNAseq (see above). Cells were washed twice in 1X PBS, then dissociated with trypsin (Hyclone) for 5 minutes. Cells

were resuspended in ice cold 1X PBS, dead cells were removed and processed for ATAC. Assay for transposase-accessible chromatin with high-throughput sequencing was performed according to the published protocol [36]. Briefly, cells were collected in cold PBS and cell membranes were disrupted in cold lysis buffer (10 mM Tris–HCl, pH 7.4, 10 mM NaCl, 3 mM MgCl2 and 0.1% IGEPAL CA-630). The nuclei were pelleted and resuspended in Tn5 enzyme and transposase buffer (Illumina Nextera® DNA library preparation kit, FC-121-1030). The Nextera libraries were amplified using the Nextera® PCR master mix and KAPA biosystems HiFi hotstart readymix successively. AMPure XP beads (Beckman Coulter) were used to purify the transposed DNA and the amplified PCR products. All libraries were sequenced on a 100 cycle paired-end run on an Illumina NOVAseq instrument. The resulting ATACseq libraries were sequenced on Illumina NovaSeq 6000 at CMG of Indiana University School of Medicine and paired-end 50 bp reads were generated. Illumina adapter sequences and low-quality base calls were trimmed off the paired-end reads with Trim Galore v0.4.3. Bowtie2 [37] was used for ATACseq reads alignment on the mouse genome (mm10). Duplicated reads were removed using Picard developed by Broad Institute [https://broadinstitute.github.io/picard/ (Accessed: 2018/02/21; version 2.17.8)]. Low mapping quality reads and mitochondrial reads were discarded in further analysis. Peak calling of mapped ATACseq reads were performed by MACS2 [38] with a Bonferroni adjusted cutoff of p-value less than 0.01. Peaks called from multiple samples were merged, after removing peaks overlapping with ENCODE blacklist regions [39, 40]. Reads locating within merged regions in different samples were counted by pyDNase [41]. The data was filtered using at least 10 cut counts in more than one of the samples, then normalized using TMM (trimmed mean of M values) method and subjected to differential analysis using edgeR (v3.24.3) [33, 42]. One sample with quality issues in the study was removed from analysis. The cutoffs used for integration of RNA-seq and ATAC-seq are: peaks withing 10kb upstream of gene, differential peak cutoff FDR < 0.05, differential expression cutoff FDR < 0.05, $\log_2$FC > 1 (up-regulation) or < -1 (down-regulation).

RNA isolation and qPCR: Bones were harvested and homogenized in 1 ml of TRIzol reagent (Invitrogen) according to the manufacturer's protocol using a Bullet Blender (Next Advance, Inc.), then further purified using the RNeasy Kit (Qiagen). RNA samples were tested with intron-spanning primers specific for mRNAs expression of gene listed. Mouse *β-actin* was used as an internal control by RT-qPCR. The qPCR primers were purchased as pre-optimized reagents (Applied Biosystems/Life Technologies, Inc.) and the TaqMan One-Step RT-PCR kit was used to perform qPCR. PCR conditions for all experiments were 30 minutes 48°C, 10 minutes 95°C, followed by 40 cycles of 15 seconds 95°C and 1 minute 60°C. The data were collected and analyzed by a StepOne Plus system (Applied Biosystems/Life Technologies, Inc.). The expression levels of mRNAs were calculated relative to appropriate controls, and the $2^{-\Delta\Delta CT}$ method described by Livak was used to analyze the data [43]. The references of the primers used in the study are below. Fgf23, Mm00445621_m1; Mmp13, Mm00439491_m1; Tnc, Mm00495662_m1; Gdpd2, Mm00469948_m1; Serping1, Mm00437835_m1; Igfbp5, Mm00516037_m1; Col1a1, Mm00801666_g1; Bglap, Mm03413826_mH; Cthrc1, Mm01163611_m1; Smpd3, Mm00491359_m1; Dmp1, Mm01208363_m1; Sost, Mm04208528_m1; Pdpn, Mm01348912_g1; Phex, Mm00448119_m1; Ptprz1, Mm00478486_m1; Adamts14, Mm01169225_gH; Pdpn(E11), Mm01348912_g1; Actin, Mm02619580_g1.

Statistical analyses: As described in Results and Methods, most recent updated R software packages with robust affiliated statistics were used to analyze the scRNAseq datasets. Statistical analyses of the *in vivo* data presented were performed by two-way ANOVA to assess the differences between the same gender in response to adenine diet to assess the differences between genders and treatments. Significant changes were considered when at $P<0.05$.

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Data availability:

scRNA-seq, RNAseq and ATAC-seq datasets will be deposited in the NCBI's Gene Expression Omnibus database.

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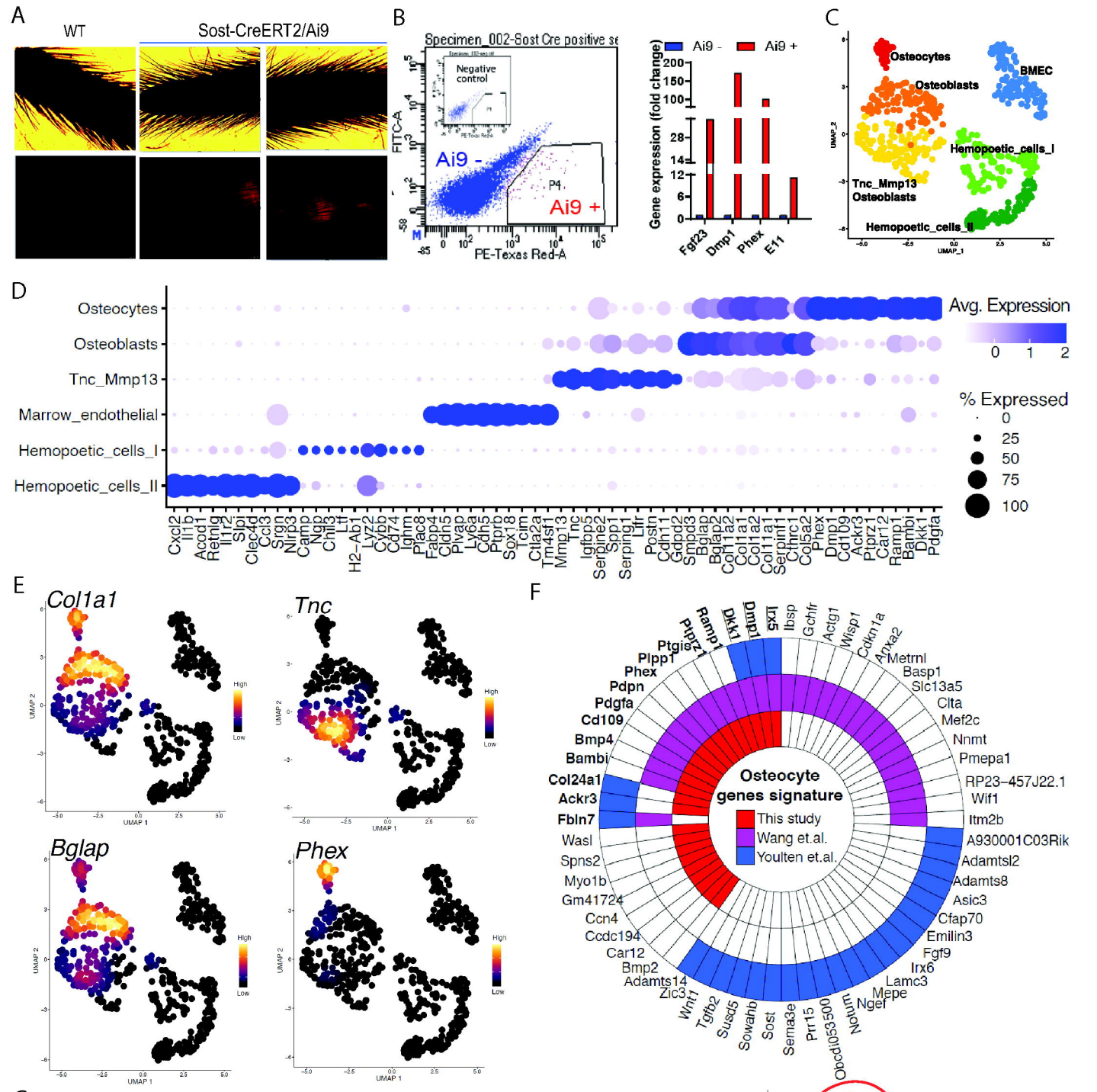
Figure 1. Single-cell transcriptomic profiling of bone cells identified osteolineage cells heterogeneity. A-B. Long bones (femur, tibia, and humeri) were subjected to serial collagenase/EDTA digestions (see methods), and cells from fractions 4-9 were collected for sorting to isolate tdTomato-positive cells followed by single-cell RNA-seq library construction. Parallel analysis confirmed a high expression of osteocyte genes *Fgf23*, *Dmp1*, *Phex*, and *Pdpn* in Ai9 positive cells *versus* Ai9 negative cells. **C.** Cell-clustering. Bioinformatic analysis was performed to cluster the cells. Each dot represents a single cell, and cells sharing the same color code indicate discrete populations of transcriptionally similar cells. **D.** Defining cell type. Tnc/Mmp13 osteoblast cells are distinctly marked by *Tnc* and *Mmp13*. Osteoblast cells show a high expression of *Smpd3* and *Bglap*. Osteocytes have the highest expression of *Dmp1* and *Phex*. **E.** Expression density plots indicate cells with high transcription *Col1a1*, *Tnc*, *Bglap*, and *Phex*. **F.** The polar figure highlights the osteocyte markers isolated from our dataset (long bone cells scRNAseq), Wang et al. (long bone and calvaria cells scRNAseq) and Youlten et al (long bone bulk RNAseq)**. G.** Canonical and non-canonical osteolineage genes were validated as being highly expressed in cortical bone when compared to the expression detected in bone marrow. **H.** Pseudotime analysis reveals Tnc/Mmp13 Osteoblasts as an osteoblast precursor (P-OB) and show their differentiation to osteoblasts (OB) and then osteocytes (OC).

Figure 2. Differential signaling pathways in osteoblasts versus osteocytes. A. Ingenuity Pathway Analysis (IPA) software was used to predict the statistically significant canonical pathways upregulated in Tnc/Mmp13 osteoblasts (P-OB), osteoblasts (OB) and osteocytes (OC) from scRNAseq data based upon a calculated probability score of ≥2 and a p-value of <0.05. Further a comparative analysis between osteolineage cells was performed to generate the heatmap. The increase of the blue intensity match with the more significant pathways in different cell types. The gray dots indicate the non-significant pathways. **B-E.** Monocle analysis shows pseudotime trajectory mapping of osteolineage gene sets *Col1a1, Col1a2, Runx2;* pre-osteoblast gene sets *Mmp13, Tnc, Spp1;* osteoblast gene sets *Bglap, Col11a2, Smpd3;* and osteocyte gene sets *Dmp1, Irx5, Ackr3, Phex, Ptprz1,* and *Cd109*. **F.** The computational method scFEA (single cell Flux Estimation Analysis) was used to infer cell-wise fluxome from single cell RNA-sequencing (scRNA-seq) data and to predict the metabolic profiling and differential metabolite conversion rate in cells that correspond to a metabolic flux value. Ridgeline plots indicate the distributions values of metabolic flux in Tnc/Mmp13 osteoblasts (P-OB), osteoblasts (OB), and osteocytes (OC). Each ridgeline represents the flux between two metabolites, shown on the x-axis, for different osteolineage cells, shown on the y-axis. **G.** The boxplots indicate the predictive value of the conversion of methionine to cysteine and to pyruvate in P-OB, OB, and OC. **H.** The barplot show the top 10 different metabolites enriched in P-OB, OB, and OC.

Figure 3. Molecular markers associated with osteoblasts/osteocytes morphogenesis change. A-top. Cartoon representing cell differentiation from MSCs to osteoblasts/osteocytes. **A-bottom.** *Col1a1*, *Sost,* and *Ptprz1* mRNAs were analyzed during osteogenic differentiation in MPC2 cells over the course of (1, 2, 3, 4 weeks) and normalized to β-actin. **B.** Volcano plots derived from bulk RNAseq dataset (left) and ATACseq dataset (right) show the significant alterations of gene expression and chromatin accessibility detected in differentiated *versus* undifferentiated cells. The x axis shows the fold-change (in $\log_2$ scale). The y axis that represents the significance. **C.** Venn diagrams highlight the numbers of genes with differentially accessible regions (DARs), or differentially expressed genes (DEGs), or both in differentiated *versus* undifferentiated cells. **D.** Integration of ATAC-seq and RNA-seq data exhibits higher correlation between genome-wide chromatin accessibility changes (x-axis) and gene expression alterations (y-axis). **E.** Functional enrichment analysis using the Database for Annotation, Visualization and Integrated Discovery (DAVID) on upregulated DEGs with more open DARs identifies biological pathways that are induced with osteogenic differentiation. The numbers in parenthesis are gene counts. **F.** Representative ATACseq peaks of undifferentiated cells (top track in gray) compared to differentiated cells (osteoblasts/osteocytes bottom track in black) are shown. **G.** Representative mRNA expression of upregulated genes in differentiated versus undifferentiated cells that are enriched in cell morphogenesis and ossification. All the genes shown were significantly upregulated (false discovery rate, FDR < 0.05). **H.** The osteocyte genes identified from scRNAseq dataset in Figure 1J were confirmed to be significantly upregulated in osteoblasts/osteocytes cells *versus* control (MSC).

Figure 4. Precocious misregulation of osteoblast/osteocyte genes in CKD. Eight weeks old C57BL/6 male (shown in blue) and female (represented in red) mice purchased from Jackson laboratories were fed an adenine diet (AD) to induce CKD for 2, or 4 weeks. Mice on casein diet for 2 weeks were used as controls. **A.** Serum biochemical analysis (phosphate, alkaline phosphatase, calcium, blood urea nitrogen, creatinine, and iron) were measured in serum using colorimetric assay. **B.** Cortical porosity (left) and trabecular bone volume (right) were measured using micro computed tomography (µCT). **C.** Representative images of cortical bone µCT. **D-E.** Cortical bone Fgf23 mRNA was measured by qPCR and circulating FGF23 was assessed by ELISA. **F-G.** Real-time PCR was used to measure the mRNA expression of Tnc/Mmp13 osteoblasts (pre-osteoblasts), osteoblasts and osteocytes gene sets. Data are shown as fold change (2-DDCt) relative to housekeeping gene *β-Actin* and normalized to the experimental control (AD 0). Data are represented as mean +/- standard deviation. *$p<0.05$, **$p<0.01$, ***$p<0.001$, ****$p<0.001$ compared to Control.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BMEC
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Avg. Expression
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Col1a1
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Bglap
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UMAP 2
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Osteocyte genes signature
This study
Wang et.al.
Youlten et.al.
Ibsp Gchfr Actg1 Wisp1 Cdkn1a Anxa2 Metrnl Basp1 Slc13a5 Clta Mef2c Nnmt Pmepa1 RP23-457J22.1 Wif1 Itm2b A930001C03Rik Adamtsl2 Adamts8 Asic3 Cfap70 Emilin3 Fgf9 Irx6 Lamc3 Mepe Ngef Notum Obcdi053500 Prr15 Sema3e Sost Sowahb Sus5 Tgfb2 Wnt1 Zic3 Adamts14 Bmp2 Car12 Ccdc194 Ccn4 Gm41724 Myo1b Spns2 Wasl Fbln7 Ackr3 Col24a1 Bambi Bmp4 Cd109 Pdgfa Pdpn Phex Plpp1 Ptgis2 Ptprz1 Ramp1 Dkk1 Dmp1 Ltx5
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BM Cells
Cortical Bone
Log2 Expression Fold Change
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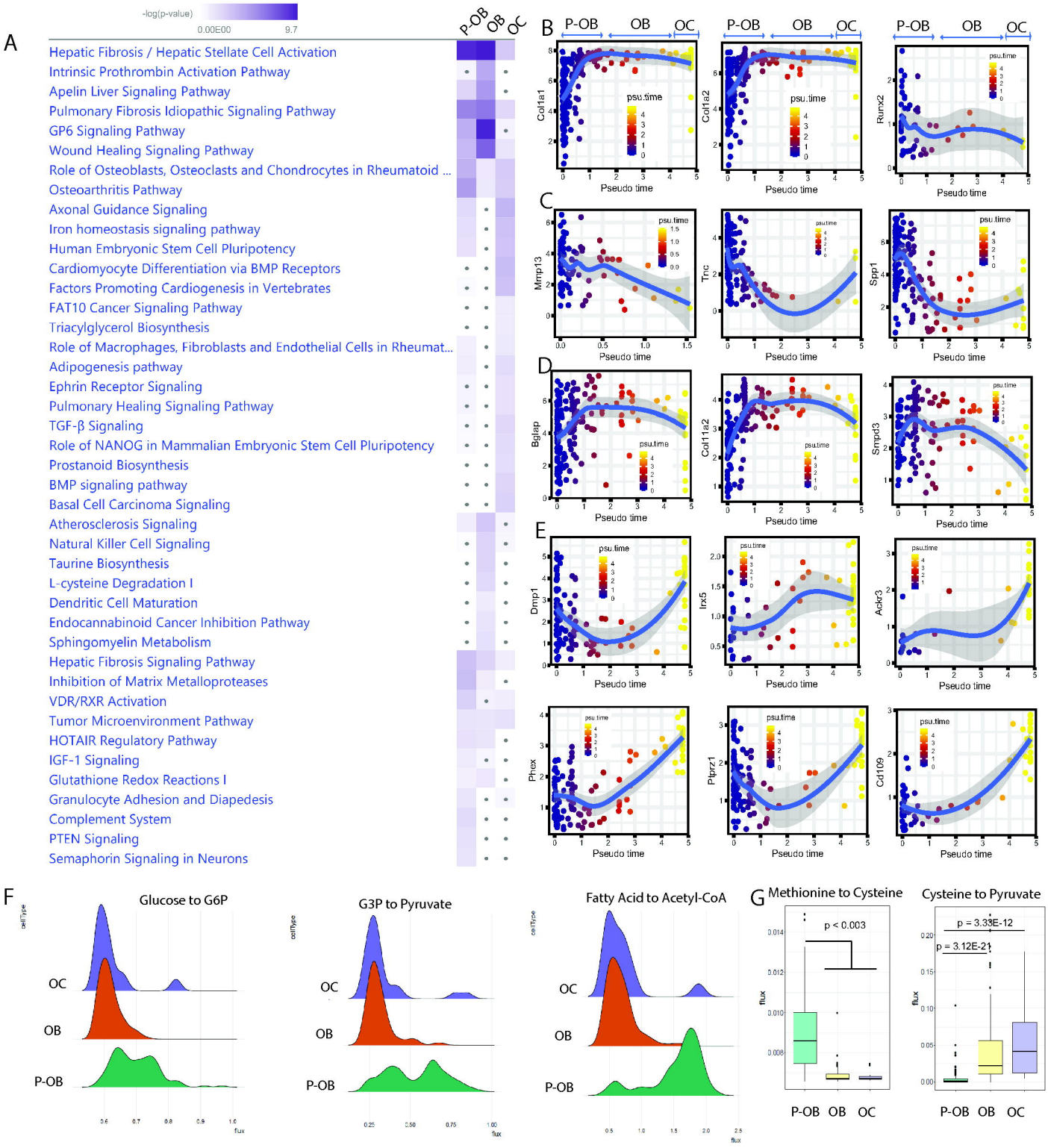
UMAP 2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Pulmonary Fibrosis Idiopathic Signaling Pathway
GP6 Signaling Pathway
Wound Healing Signaling Pathway
Role of Osteoblasts, Osteoclasts and Chondrocytes in Rheumatoid ...
Osteoarthritis Pathway
Axonal Guidance Signaling
Iron homeostasis signaling pathway
Human Embryonic Stem Cell Pluripotency
Cardiomyocyte Differentiation via BMP Receptors
Factors Promoting Cardiogenesis in Vertebrates
FAT10 Cancer Signaling Pathway
Triacylglycerol Biosynthesis
Role of Macrophages, Fibroblasts and Endothelial Cells in Rheumat...
Adipogenesis pathway
Ephrin Receptor Signaling
Pulmonary Healing Signaling Pathway
TGF-β Signaling
Role of NANOG in Mammalian Embryonic Stem Cell Pluripotency
Prostanoid Biosynthesis
BMP signaling pathway
Basal Cell Carcinoma Signaling
Atherosclerosis Signaling
Natural Killer Cell Signaling
Taurine Biosynthesis
L-cysteine Degradation I
Dendritic Cell Maturation
Endocannabinoid Cancer Inhibition Pathway
Sphingomyelin Metabolism
Hepatic Fibrosis Signaling Pathway
Inhibition of Matrix Metalloproteases
VDR/RXR Activation
Tumor Microenvironment Pathway
HOTAIR Regulatory Pathway
IGF-1 Signaling
Glutathione Redox Reactions I
Granulocyte Adhesion and Diapedesis
Complement System
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D
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Col1a2
Runx2
Mmp13
Tnc
Spp1
Bglap
Col11a2
Smpd3
Dmp1
Irx5
Ackr3
Phex
Ptprz1
Cd109
F
Glucose to G6P
G3P to Pyruvate
Fatty Acid to Acetyl-CoA
cellType
OC
OB
P-OB
flux
G
Methionine to Cysteine
Cysteine to Pyruvate
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Succinyl.CoA
Pyrimidine
AICAR
Propanoyl.CoA
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CDP
Malate
X.Glc.3..GlcNAc
X.Gal.2..GlcA
dCMP
Xanthine
X2OG
Succinate
Lactate
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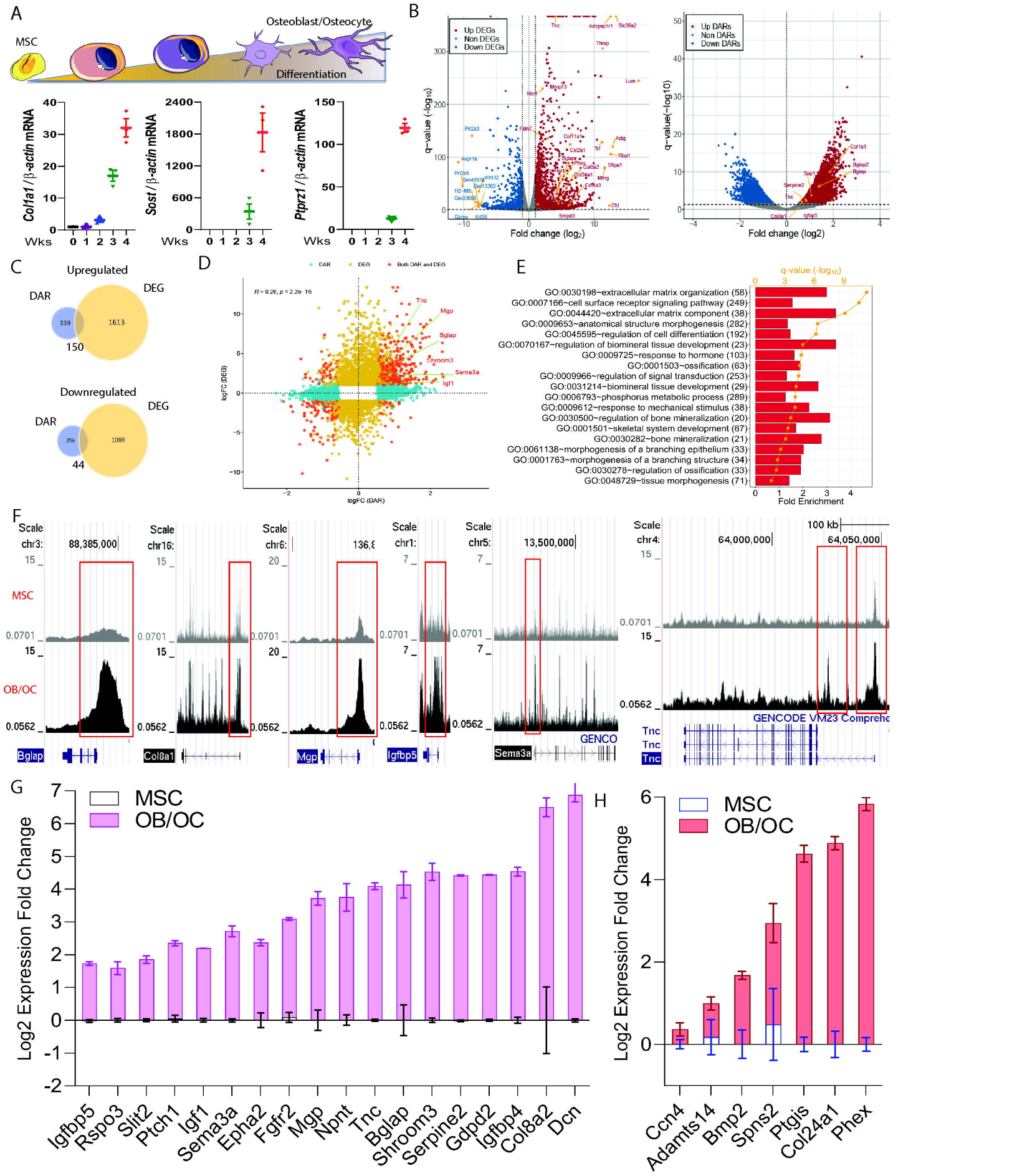
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MSC
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Differentiation
Col1a1 / β-actin mRNA
Sost / β-actin mRNA
Ptprz1 / β-actin mRNA
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Non DEGs
Down DEGs
q-value (-log10)
Fold change (log2)
Up DARs
Non DARs
Down DARs
q-value(-log10)
C
Upregulated
DAR
DEG
339
1613
150
Downregulated
356
1089
44
D
DAR
DEG
Both DAR and DEG
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Bglap
Shroom3
Sema3a
Igf1
E
q-value (-log10)
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GO:0030282~bone mineralization (21)
GO:0061138~morphogenesis of a branching epithelium (33)
GO:0001763~morphogenesis of a branching structure (34)
GO:0030278~regulation of ossification (33)
GO:0048729~tissue morphogenesis (71)
Fold Enrichment
F
Scale
chr3:
88,385,000
chr16:
chr6:
chr1:
chr5:
13,500,000
chr4:
64,000,000
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MSC
OB/OC
Bglap
Col8a1
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GENCODE VM23 Comprehe
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MSC
OB/OC
Log2 Expression Fold Change
Igfbp5
Rspo3
Slit2
Ptch1
Igf1
Sema3a
Epha2
Fgfr2
Mgp
Npnt
Tnc
Bglap
Shroom3
Serpine2
Gdpd2
Igfbp4
Col8a2
Dcn
H
MSC
OB/OC
Log2 Expression Fold Change
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Adamts14
Bmp2
Spns2
Ptgis
Col24a1
Phex

A
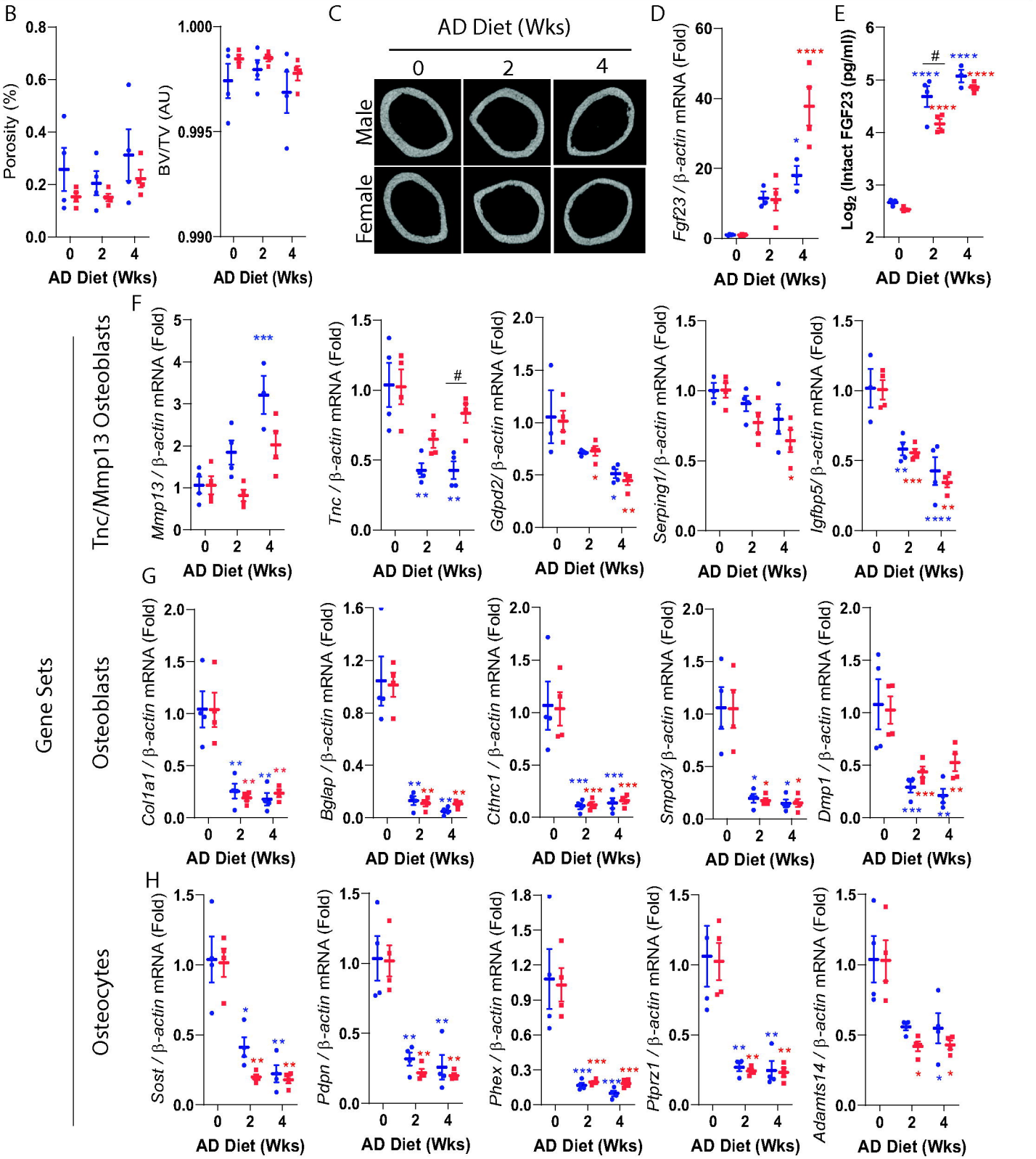
Table 1. Serum biochemical analysis						
	Male			Female		
	Ctl	Adenine 2 weeks	Adenine 4 weeks	Ctl	Adenine 2 weeks	Adenine 4 weeks
Pi (mg/dL)	12.22 ± 1.49	15.01 ± 0.95	17.23 ± 1.39[A]	12.53 ± 1.55	12.85 ± 1.45	14.88 ± 1.74
ALP (U/L)	103.75 ± 21.02	95 ± 10.66	113.75 ± 17.09	131.25 ± 34.16	88.75 ± 8.92	105 ± 11.18
Ca (mg/dL)	11.2 ± 0.29	11.86 ± 0.43	10.25 ± 1.28	10.5 ± 0.32	11.08 ± 0.62	11.26 ± 0.69
BUN (mg/dL)	64.51 ± 15.63	140.00 ± 23.11[B]	176.26 ± 66.17[C]	56.15 ± 6.62	115.88 ± 13.61	175.54 ± 29.14[C]
Creatinine mg/dL)	0.40 ± 0.19	0.69 ± 0.13	0.71 ± 0.20	0.50 ± 0.08	0.65 ± 0.11	0.71 ± 0.06
Iron (μM)	37.13 ± 7.81	15.38 ± 6.05[B]	23.75 ± 4.48[A]	28.38 ± 7.81	8.88 ± 4.44[B]	12.38 ± 2.88[A]
Data presented as mean ± SD. N = 4 mice per group. [A]p < 0.05; [B]p < 0.01; [C]p < 0.001 vs. Control (Ctl)