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Aging impairs cold-induced beige adipogenesis and adipocyte metabolic reprogramming

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Abstract

The energy-burning capability of beige adipose tissue is a potential therapeutic tool for reducing obesity and metabolic disease, but this capacity is decreased by aging. Here, we evaluate the impact of aging on the profile and activity of adipocyte stem and progenitor cells (ASPCs) and adipocytes during the beiging process. We found that aging increases the expression of *Cd9* and other fibrogenic genes in fibroblastic ASPCs and blocks their differentiation into beige adipocytes. Fibroblastic ASPC populations from young and aged mice were equally competent for beige differentiation *in vitro*, suggesting that environmental factors suppress adipogenesis *in vivo*. Examination of adipocytes by single nucleus RNA-sequencing identified compositional and transcriptional differences in adipocyte populations with age and cold exposure. Notably, cold exposure induced an adipocyte population expressing high levels of *de novo* lipogenesis (DNL) genes, and this response was severely blunted in aged animals. We further identified natriuretic peptide clearance receptor *Npr3*, a beige fat repressor, as a marker gene for a subset of white adipocytes and an aging-upregulated gene in adipocytes. In summary, this study indicates that aging blocks beige adipogenesis and dysregulates adipocyte responses to cold exposure and provides a unique resource for identifying cold and/or aging-regulated pathways in adipose tissue.

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Introduction

Brown and beige fat cells are specialized to burn calories for heat production in response to certain stimuli and have the capacity to reduce obesity and metabolic disease. Brown adipocytes are localized in dedicated brown adipose tissue (BAT) depots, whereas beige adipocytes develop in white adipose tissue (WAT) in response to cold exposure, and other stimuli (W. Wang & Seale, 2016). Adult humans possess thermogenic adipose depots that resemble rodent beige adipose tissue (Jespersen et al., 2013; Wu et al., 2012). Brown and beige adipocytes share similar cellular features such as abundant mitochondria, multilocular lipid droplets, and expression of thermogenic genes like Uncoupling Protein-1 (UCP1). UCP1, when activated, dissipates the mitochondrial proton gradient, leading to high levels of substrate oxidation and heat production (Cannon & Nedergaard, 2004). Brown and beige adipocytes can also produce heat via several other UCP1-independent futile cycles (Chouchani, Kazak, & Spiegelman, 2019).

Increasing beige fat development in mice reduces obesity and improves insulin sensitivity, whereas ablation of beige fat in mice causes metabolic dysfunction (Cederberg et al., 2001; Cohen et al., 2014; Seale et al., 2011; Shao et al., 2016; Stine et al., 2016). Furthermore, transplantation of human beige adipocytes into obese mice reduces liver steatosis and improves metabolic health (Min et al 2016). Beige adipocytes develop via the *de novo* differentiation of adipocyte precursor cells (ASPCs) or through induction of the thermogenic program in adipocytes (Ferrero, Rainer, & Deplancke, 2020; Sakers, De Siqueira, Seale, & Villanueva, 2022; Shao et al., 2019).

Human and mouse thermogenic adipose tissue activity declines with aging, predisposing to cardiometabolic disease and limiting the potential of brown/beige fat targeted therapies (Becher et al., 2021; Berry et al., 2017; Cypess et al., 2012; Rogers, Landa, Park, & Smith, 2012; W. Wang et al., 2019; Yoneshiro et al., 2011). In mice, beige adipose tissue is reduced by ‘middle-age’ (i.e., 1-year-old), preceding many of the damaging effects of old age on organ function (Berry et al., 2017; Goncalves et al., 2017; Rogers et al., 2012). The aging-associated decline in beige fat activity can occur independently of increases in body weight (Rogers et al., 2012; St-Onge, 2005). A variety of processes and pathways have been linked to the aging-induced deficit in beige fat formation, including diminished proliferation and cellular senescence of ASPCs (Berry et al., 2017), increased fibrosis (W. Wang et al., 2019), increased inflammation (Amiya Kumar Ghosh, 2019), accumulation of anti-adipogenic regulatory cells (Nguyen et al., 2021), and reduced adrenergic tone (Rogers et al., 2012). However, a detailed understanding of how cold exposure and aging affect ASPC identity, adipogenesis, and adipocyte phenotypic switching remains elusive.

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We applied ASPC lineage tracing, along with unbiased single-cell and single-nucleus RNA sequencing (scRNA-seq; snRNA-seq) to comprehensively profile the beiging process and evaluated the impact of aging on this process. We found that aging modulates the gene program of multiple fibroblastic ASPC populations and blocks the differentiation of these cells into beige adipocytes *in vivo*. snRNA-seq analysis revealed four types of adipocytes defined by different responses to cold exposure and aging: beige, Npr3-high, *de novo* lipogenesis (DNL)-low, and DNL-high. Notably, DNL-high adipocytes were defined by the marked induction of DNL genes during cold exposure in young compared to aged animals. A white adipocyte subpopulation in young mice were marked by expression of Natriuretic peptide receptor-3 (*Npr3*), which was also increased in multiple adipocyte populations of aged mice. Altogether, this study shows that aging blocks cold-stimulated adipocyte reprogramming and ASPC adipogenesis and implicates suppression of natriuretic peptide signaling and DNL in contributing to the aging-mediated decline in beige fat formation.

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Results

Figure 1

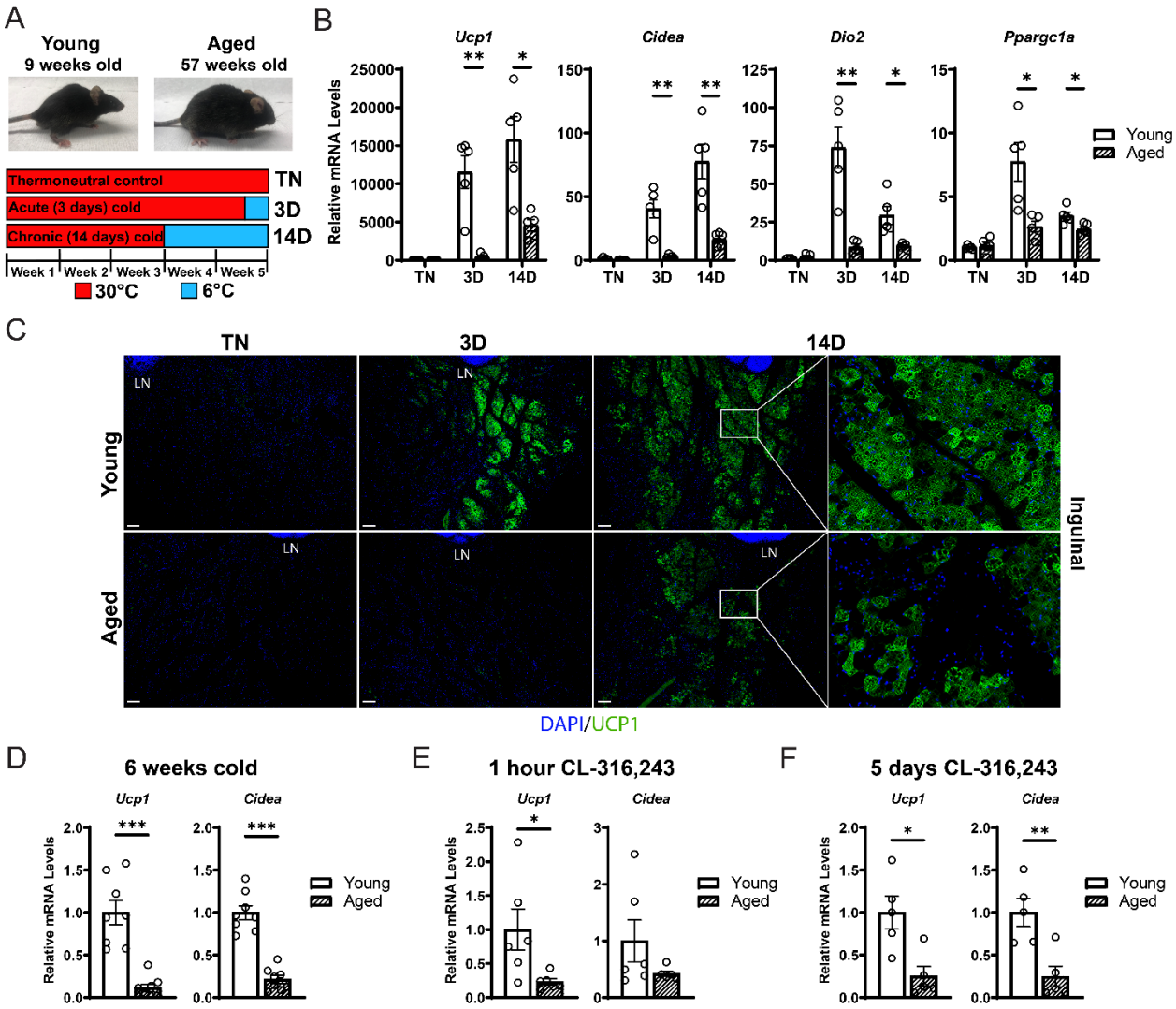

Figure 1. Aged mice exhibit decreased iWAT beiging in response to cold exposure or β3-agonist treatment. (**A**) Young (9-week-old) and aged (57-week-old) C57BL/6 mice were acclimated to 30°C for 3 weeks, followed by two additional weeks remaining at 30°C (TN, thermoneutral controls), spending the last 3 days at 6°C (3D, acute cold) or last 14 days at 6°C (14D, chronic cold). (**B**) Relative mRNA levels of thermogenic marker genes in mouse iWAT from (A), n=5. (**C**) Immunofluorescence analysis of UCP1 (green) and DAPI (blue) in iWAT sections from mice in (A), LN = lymph node. Scale bar 100 µm. (**D-F**) Relative mRNA levels of *Ucp1* and *Cidea* in iWAT from young and aged mice that were either: exposed to 6°C cold for 6 weeks (D), treated with CL-316,243 for 1 hour (E) or treated with CL 316,243 for 5 days (F). Data represent mean ± SEM, points represent biological replicates, 2 groups analyzed using a Student's t-test, and multiple conditions analyzed with a Holm-Šidák correction for multiple comparisons. Significance: not significant, P > 0.05; * P < 0.05 ** P < 0.01; *** P < 0.001.

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Aging impairs iWAT beiging

To study the impact of aging on beige adipose tissue development, we exposed young (9-week-old) and middle aged (57-week-old) C57BL/6 mice to 6°C for either 3 or 14 days. All mouse groups were first acclimated to 30°C (thermoneutrality [TN]) for 3 weeks to reduce beige adipose tissue to baseline (low) levels. Following acclimation, TN-housed mice remained at 30°C; acute cold mice (3D) were transitioned to 6°C after 11 days for the final 3 days; and chronic cold mice (14D) were moved to 6°C for two weeks (***Figure 1A***). As expected, the aged mice weighed more and had larger iWAT depots than the young mice (***Figure S1A,B***). Cold exposure greatly and progressively increased the expression levels of thermogenic genes *Ucp1*, *Cidea*, *Dio2* and *Ppargc1a* in young iWAT, but the activation of these genes was significantly blunted in aged mice, especially at the 3D timepoint (***Figure 1B***). Immunofluorescence staining showed a robust induction of UCP1 protein in multilocular adipocytes of young iWAT at 3D of cold exposure, which was further increased at 14D. The induction of UCP1^{+} beige adipocytes was severely reduced in aged animals, with strikingly few UCP1+ adipocytes detected at. At 14D, the beige adipocytes in young and aged look morphologically similar, although there are fewer in aged. (***Figure 1C***). Beige adipocytes in young and aged were most prominent in the inguinal region (versus dorsolumbar) of iWAT, consistent with other reports (Barreau et al., 2016; Chi et al., 2018; Dichamp et al., 2019) and beiging was largely absent in the dorsolumbar region of aged mice (***Figure S1C-D***). To determine if the beiging response is delayed in aged mice, we exposed young and aged mice at 6°C for 6 weeks. At this time point, the iWAT of aged mice exhibited a larger deficit in thermogenic gene expression compared to young animals (***Figure 1D***). Thermogenic gene levels in interscapular BAT were similar between young and aged mice, at TN and after cold exposure, indicating that the inhibitory effects of aging were selective to WAT (***Figure S1E***).

Next, we examined beige fat formation in young and aged animals upon treatment with the β3-selective adrenergic agonist CL-316,243 (CL). CL acts in an adipose tissue autonomous manner to stimulate beige fat biogenesis, bypassing the central nervous system pathways that mediate the response to cold exposure. Acute CL treatment for only 1 hour increased iWAT *Ucp1* expression in young mice to a much greater extent than in aged mice (***Figure 1E***). Chronic CL exposure for 5 days also induced much higher expression levels of *Ucp1* and *Cidea* in iWAT of young compared to aged mice (***Figure 1F***). Taken together, these results demonstrate that beige adipose tissue induction is severely impaired in middle aged mice.

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Figure 2

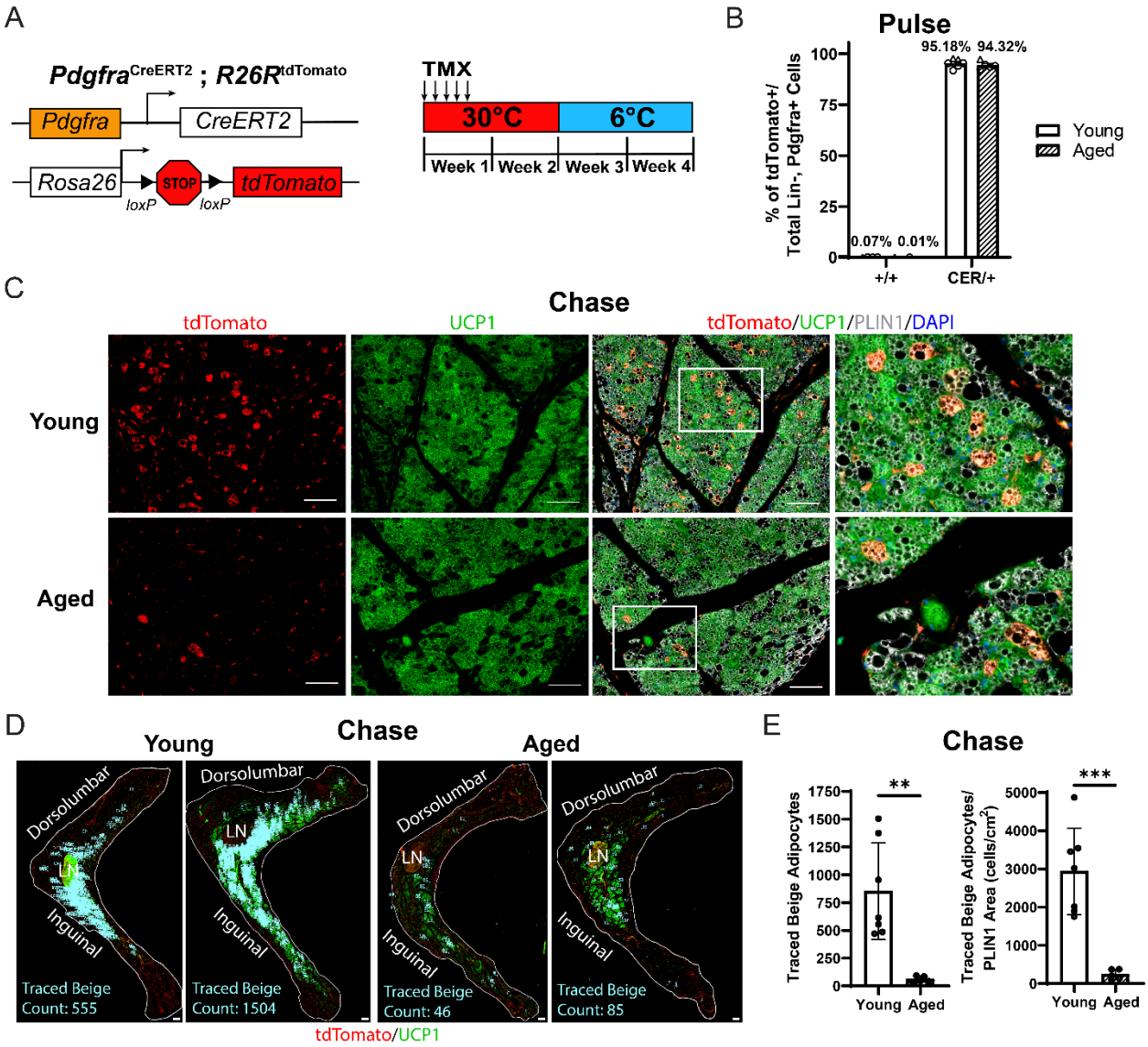

Figure 2. Aging blocks beige adipogenesis from fibroblastic ASPCs.

(**A**) Schematic of *Pdgfra*^{CreERT2};*R26R*^{tdTomato} reporter mouse model and lineage tracing paradigm. (**B**) Flow cytometry-based quantification showing proportion of tdTomato-expressing PDGFRα^{+}cells (as % of total Live, Lin-, PDGFRα^{+} cells) in iWAT from young and aged Cre^{+} and Cre^{-} (control) mice. n=6 young, 5 aged (Circles represent male mice, triangles represent female mice). (**C**) Immunofluorescence analysis of tdTomato (red), UCP1 (green), PLIN1 (white) and DAPI (blue) in iWAT from young and aged reporter mice after 14 days of 6°C cold exposure (chase). Scale bar 100 µm. (**D**) Representative stitched images of full length iWAT histology slices from samples in (C) showing quantification of traced tdTomato^{+};UCP1^{+} multilocular (beige) adipocytes (blue numbers). LN= lymph node, scale bar 500 µm. (**E**) Quantification of traced beige adipocytes from (D) presented as total cell number (left) or proportion of PLIN1^{+} area (right), n=7 (young), n=5 (aged). Data represent mean ± SEM, points represent biological replicates, 2 groups analyzed using a Student's t-test, and multiple conditions analyzed with a Holm-Šidák correction for multiple comparisons. Significance: not significant, P > 0.05; * P < 0.05 ** P < 0.01; *** P < 0.001..

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Aging blocks beige adipogenesis from *Pdgfra*$^+$ ASPCs

To determine the contribution of fibroblastic ASPCs to beige adipocytes during cold exposure, we performed lineage tracing using *Pdgfra-Cre*^{ERT2};*R26R*^{tdTomato} reporter mice. *Pdgfra* expression marks multiple ASPC populations, including preadipocytes (Merrick et al., 2019; Sakers et al., 2022). Young and aged reporter mice were treated with tamoxifen for 5 days at TN (30°C; "pulse") to activate Cre and induce tdTomato expression in *Pdgfra*$^+$ cells. Following a 9 day washout period, mice were transferred to 6°C (cold) for two weeks ("chase") (***Figure 2A***). We observed near complete and specific labeling of ASPCs during the pulse period, with ~95% of PDGFRα$^+$ cells in iWAT from young and aged mice displaying tdTomato expression (***Figures 2B, S2A***). No tdTomato-expressing adipocytes were observed after the pulse (***Figure S2B***). After 14 days of cold exposure, we detected many newly developed beige adipocytes from ASPCs in young mice (visible as tdTomato$^+$/UCP1$^+$ multilocular adipocytes). By contrast, very few ASPC-derived (tdTomato$^+$) were detected in the beige fat areas of aged iWAT at day 14 (***Figures 2C***). Quantifying across the entire length of iWAT pads revealed that most beige adipogenesis occurred in the inguinal region and was ~12-fold lower in aged than in young (***Figure 2D,E***). However, the overall contribution of *Pdgfra*$^+$ ASPCs to beige adipocytes was relatively low, even in young animals, with <20% of beige adipocytes expressing tdTomato.

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Figure 3

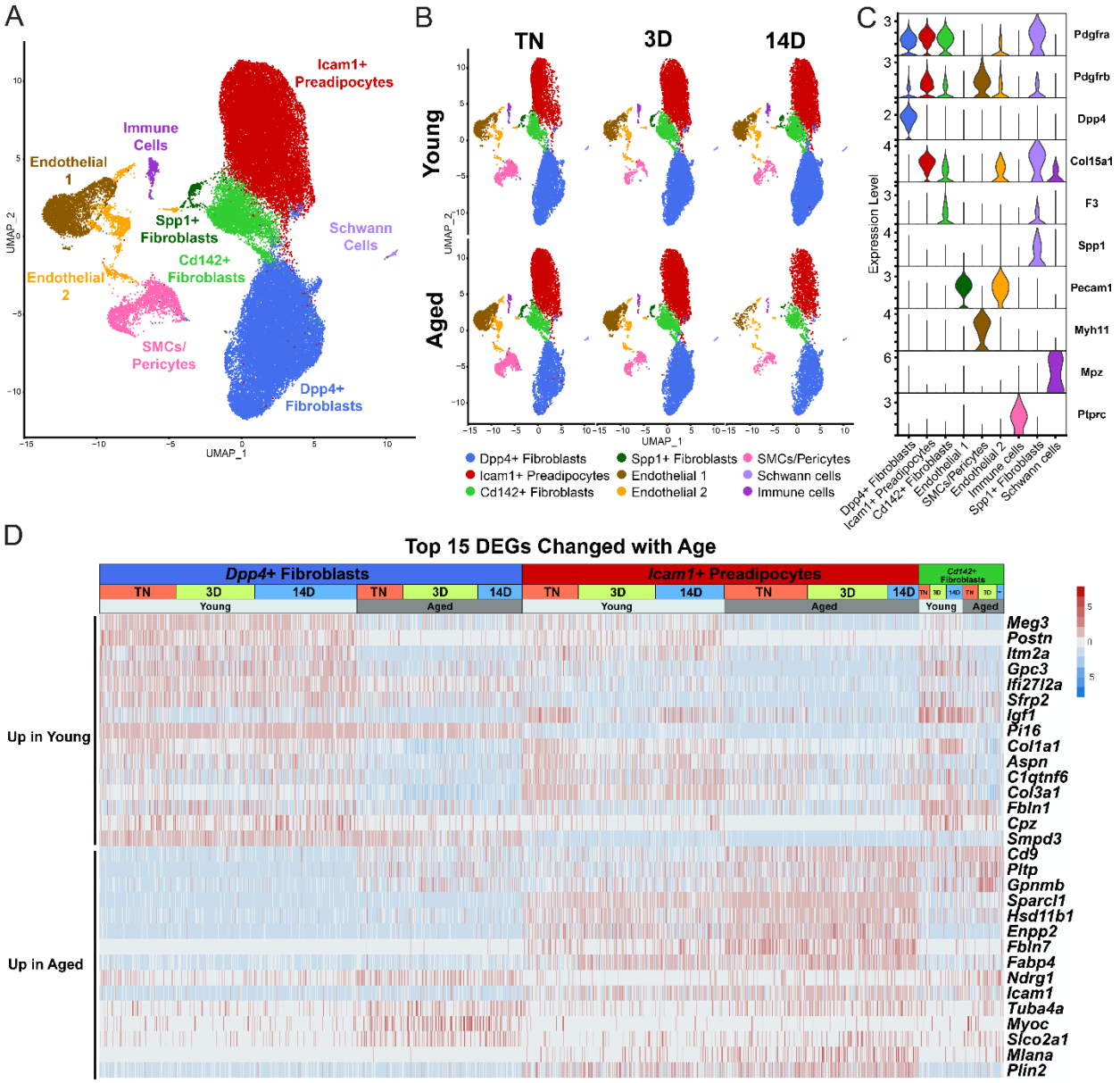

Figure 3. Single cell expression profiling of ASPCs during iWAT beiging.

(**A**) Fully integrated UMAP of gene expression in 54,987 stromal vascular cells (FACS depleted of CD45$^+$ immune cells) from young and aged mouse groups detailed in Figure 1A. (**B**) UMAPs split by condition. (**C**) Violin plots showing the expression levels of representative marker genes for various cell clusters. y-axis = log-scale normalized read count. (**D**) Expression heatmap of the top differentially expressed genes in young vs. aged fibroblastic ASPCs (combined *Dpp4*$^+$, preadipocytes and *Cd142*$^+$ cells). Table shows expression of these genes in ASPC populations across temperature conditions (TN, cold 3D, cold 14D) from young and aged mice.

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Single cell expression profiling of ASPCs

We previously identified three main fibroblastic ASPC populations in iWAT: DPP4$^+$ interstitial cells, ICAM1$^+$ preadipocytes, and CD142$^+$ cells. All these cell types express *Pdgfra* and have the capacity to undergo adipogenic differentiation (Merrick et al., 2019). We hypothesized that the aging-related impairment of beige adipogenesis was caused by dysregulation of these ASPC types. To investigate this, we performed scRNA-seq on stromal vascular cells from iWAT of young and aged animals, maintained at TN, or following transition to cold for 3 or 14 days (***Figure 1A***). ASPCs were enriched by removing immune (CD45$^+$) cells using fluorescence activated cell sorting (FACS). We integrated the datasets from all conditions together and performed clustering analysis. The following cell populations were annotated based on their expression of cell type-specific marker genes: four fibroblast populations (*Dpp4*$^+$; *Icam1*$^+$ preadipocytes; *Cd142*$^+$, *Spp1*$^+$), two populations of endothelial cells (*Pecam1*$^+$); smooth muscle cells/pericytes (*Myh11*$^+$, *Pdgfrb*$^+$); Schwann cells (*Mpz*$^+$); and residual immune cells (*Ptprc*$^+$) (***Figures 3A-C***). Aging or cold exposure did not promote the emergence of any specific cell populations. In this regard, we did not identify 'aging-dependent regulatory cells (ARCs)', which were previously defined as ASPCs expressing *Lgals3* and other inflammatory genes (***Figure S3A***) (Nguyen et al., 2021). The expression levels of identity markers of the ASPC populations were not modulated during cold exposure or aging (***Figure S3B***).

Differential gene expression analyses identified aging-modulated genes in the ASPC populations (***Figure 3D***). Notably, expression of *Cd9*, previously identified as a fibrogenic marker, was upregulated with age in *Dpp4*$^+$ cells and preadipocytes (Marcelin et al., 2017). *Pltp* and *Gpnmb* were also elevated by aging across all ASPC populations and temperature conditions. Genes downregulated by aging in all ASPC populations included *Meg3*, *Itm2a* and *Gpc3 and Postn*. Of note, *Postn* encodes an extracellular matrix protein that was previously reported to regulate adipose tissue expansion and decrease in expression during aging (Graja et al., 2018).

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Figure 4

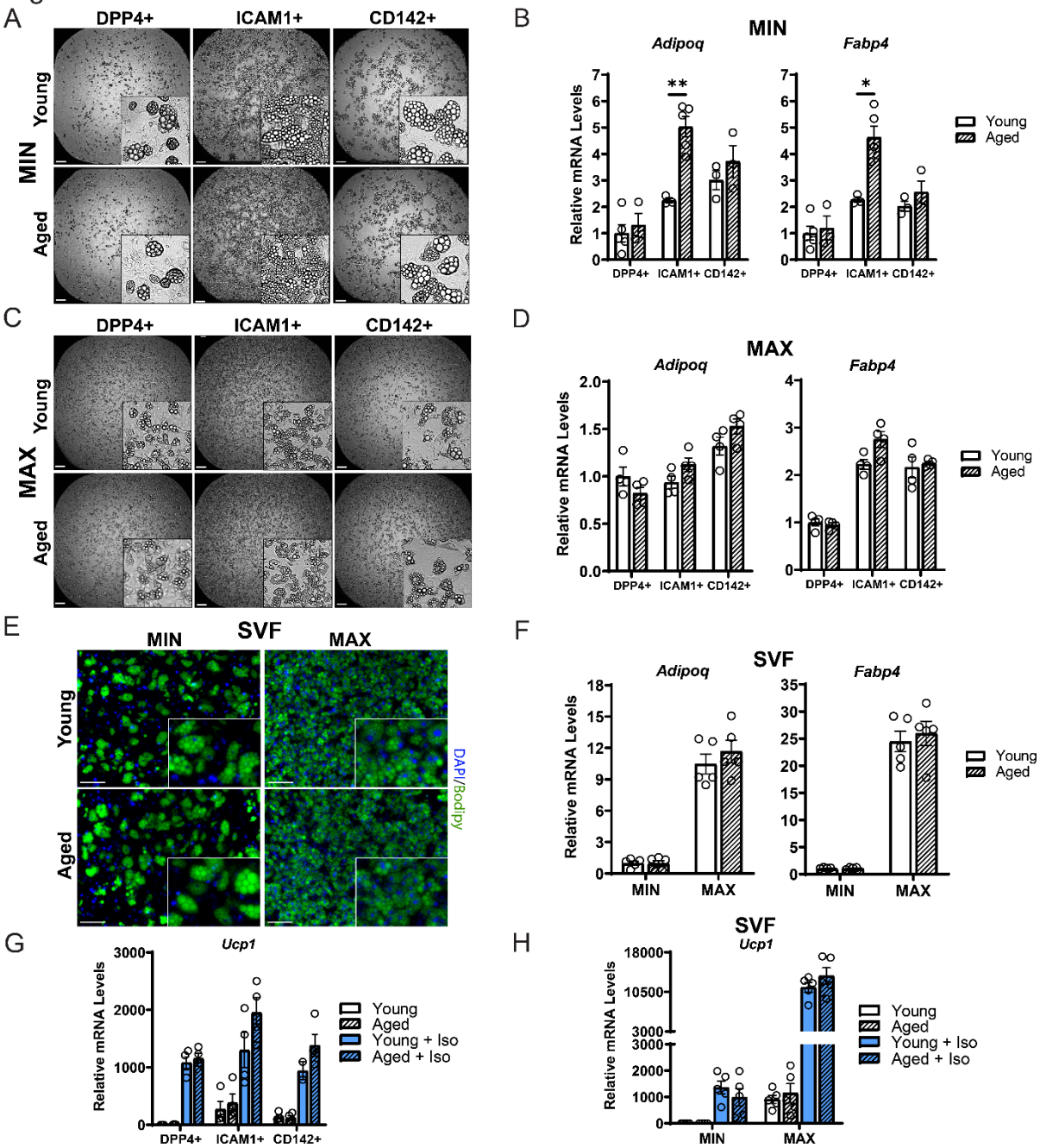

Figure 4. ASPCs from young and aged mice display similar beige adipogenic activity *ex vivo*. (**A, C**) Phase contrast images of DPP4$^+$, ICAM1$^+$ and CD142$^+$ cells from iWAT of young and aged mice that were induced to undergo adipocyte differentiation with minimal (MIN, A) or maximal (MAX, C) induction cocktail for 8 days. Scale bar 200 µm. (**B, D**) mRNA levels of adipocyte marker genes *Adipoq* and *Fabp4* in cultures from (A, C). Data points represent separate wells, sorted from a pool of 5 mice (A) or sorted from two pools of 2-3 mice (C). (**E**) Stromal vascular fraction (SVF) cell cultures from the iWAT of young and aged mice were induced to differentiate for 8 days with MIN or MAX cocktail, followed by Bodipy (green) staining of lipid droplets and DAPI (blue) staining of nuclei. Scale bar 100 µm. (**F**) Relative mRNA levels of *Adipoq* and *Fabp4* in cultures from (E). Data points represent wells from individual mice, n = 5. (**G, H**) Relative mRNA levels of *Ucp1* in adipocyte cultures from (C, E) with or without treatment with isoproterenol for 4 hours. Data points represent wells sorted from two pools of 2-3 mice

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(G) or wells from individual mice, n=5 (H). Data represent mean ± SEM, 2 groups analyzed using a Student's t-test, and multiple conditions analyzed with a Holm-Šidák correction for multiple comparisons. Significance: not significant, P > 0.05; * P < 0.05 ** P < 0.01; *** P < 0.001.

ASPCs from aged mice are competent for beige adipogenesis *ex vivo*

We next evaluated if ASPCs from young and aged animals exhibit cell-autonomous differences in adipogenic differentiation capacity. We FACS-purified the three ASPC populations, DPP4$^+$, ICAM1$^+$ and CD142$^+$ cells, from the iWAT of young and aged mice, plated them in culture and induced adipocyte differentiation. Using a minimal differentiation stimulus consisting of insulin only (MIN), ICAM1$^+$ and CD142$^+$ cells underwent more efficient differentiation into lipid droplet-containing adipocytes, and expressed higher levels of adipocyte genes (*Adipoq* and *Fabp4*) than DPP4$^+$ cells, consistent with prior work (***Figures 4A,B***) (Merrick et al., 2019). DPP4$^+$ and CD142$^+$ cells from young and aged mice underwent adipocyte differentiation and induced adipocyte genes with equivalent efficiency. Unexpectedly, aged ICAM1$^+$ cells exhibited greater differentiation capacity than young ICAM1$^+$ cells, as evidenced by higher expression levels of *Adipoq* and *Fabp4* (***Figures 4A,B***). Maximal stimulation with a full cocktail of adipogenic inducers (MAX), produced similar and robust differentiation in all ASPC populations from young or aged mice (***Figures 4C,D***). To assess whether young and aged precursor cells behave differently when cultured as a mixed heterogeneous population, we isolated the stromal vascular fraction (SVF) for adipogenesis assays. Again, SVF cell cultures from both young and aged mice displayed similar adipogenic differentiation capacity with either MIN or MAX stimulation (***Figures 4E,F***). Finally, we stimulated cell cultures with the pan-adrenergic agonist isoproterenol for 4 hours to evaluate thermogenic gene activation (i.e., beiging). Basal levels of *Ucp1* expression appear to be lower in DPP4$^+$ cells compared to other ASPC types, but all three ASPC populations activated *Ucp1* expression to high and similar levels in response to stimulation and did not differ by age (***Figure 4G***). We also did not observe an aging-related difference in the levels of *Ucp1* induction in SVF-derived adipocyte cultures stimulated with either MAX or MIN cocktail, and as expected, MAX differentiated cells demonstrated greater stimulated capacity (***Figure 4H***). Together, these data suggest that the beige adipogenic capacity of ASPCs is not intrinsically compromised in aged mice, and therefore the *in vivo* deficit in beige adipogenesis could be due to non-ASPC-autonomous effects.

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Figure 5

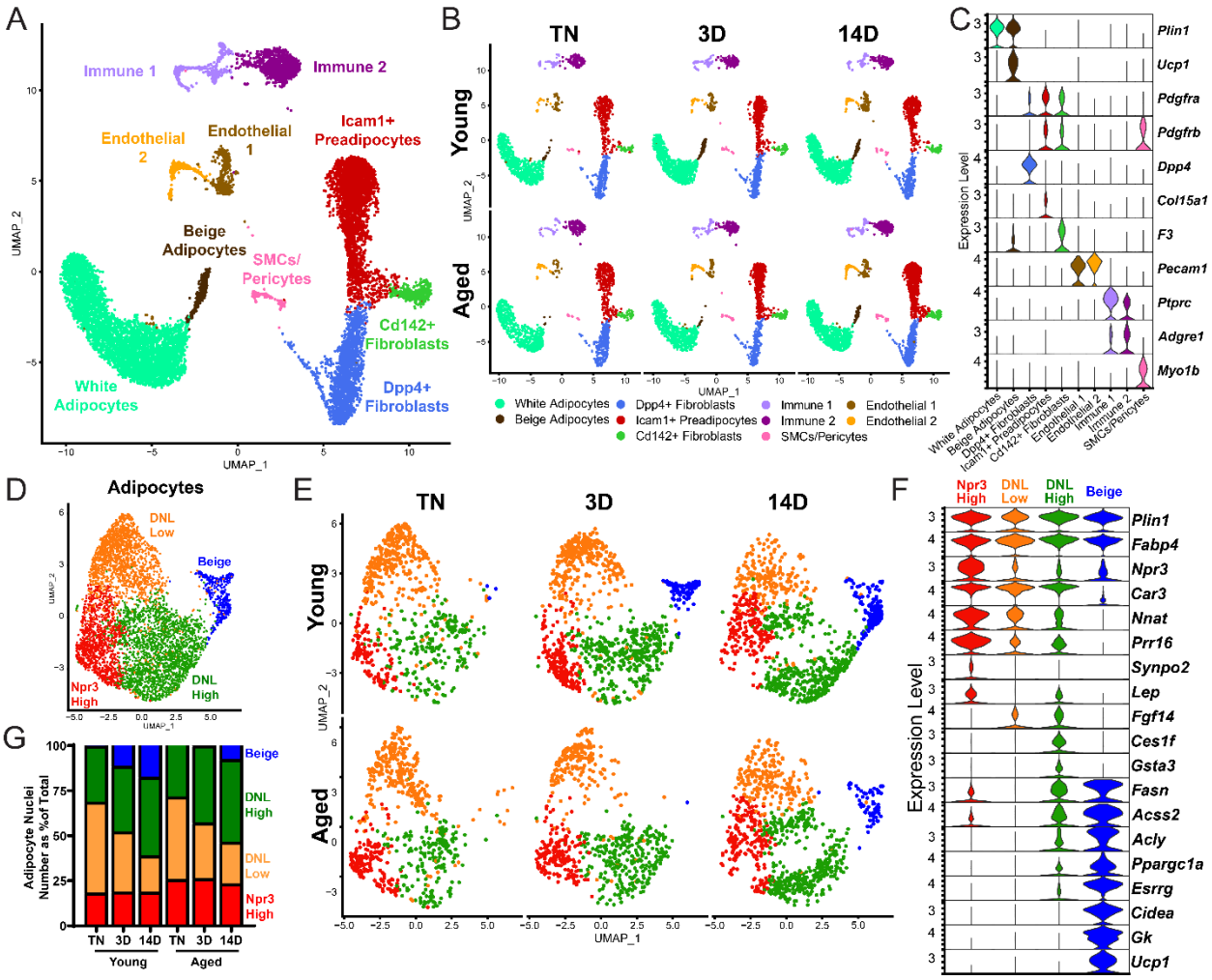

Figure 5. Single nucleus expression profiling of adipocytes during the beiging process in young and aged mice. (**A**) Fully integrated UMAP of mRNA levels in 11,905 nuclei from iWAT of mouse groups detailed in Figure 1A, n=2 mice per condition. (**B**) UMAPs split by condition. (**C**) Violin plots showing expression patterns of cell cluster-selective marker genes, Y-axis = log-scale normalized read count. (**D**) UMAP of gene expression in re-integrated adipocyte clusters including 4,937 nuclei from (A) identifying four populations: Npr3-high, beige, DNL-low, and DNL-high. (**E**) Adipocyte UMAPs split by condition. (**F**) Violin plots showing expression patterns of selected genes in adipocyte populations, Y-axis = log-scale normalized read count. (**G**) Adipocyte nuclei numbers in each sample, plotted as percent of total adipocytes captured for that sample.

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Single nucleus RNA sequencing uncovers adipocyte heterogeneity

To determine the effects of aging and cold exposure on adipocyte gene profiles, we performed snRNA-seq analyses of iWAT samples using the same experimental paradigm described above (***Figure 1A)***. We integrated all the conditions together for analyses from two separate runs. Similar cell types were captured as with scRNA-seq (***Figure 3A***), but with the addition of mature adipocyte populations (***Figure 5A***). This dataset has increased representation from immune cells since there was no negative selection against CD45$^+$ cells. As with the single-cell data set, we did not identify any aging-specific cell populations (***Figure S4A***). However, we observed striking differences in the adipocyte cluster across age and temperature. Most obvious was the emergence and expansion of a distinct beige adipocyte population, marked by expression of *Ucp1* and other thermogenic genes, during cold exposure (***Figure 5B***).

To focus on adipocyte responses, we reintegrated the snRNA-seq data using only the adipocytes, which revealed four main clusters (***Figures 5D-F***). Beige adipocytes, marked by high expression of many thermogenic genes (i.e., *Ppargc1a*, *Esrrg*, *Cidea*, *Gk* and *Ucp1*), were the most distinctive cluster and were largely absent at TN in young and aged mice, but they began to appear in young mice after 3 days of cold exposure, and were further increased at 14 days. By contrast, in aged mice, beige cells were barely detectable at 3 days of cold exposure and were present at greatly reduced numbers than in young mice at 14 days (***Figure 5E***). This analysis also revealed three sub-populations of 'white' adipocytes. '*Npr3*-high' adipocytes were enriched for expression of *Npr3*, *Synpo2*, *Prr16*, and *Tshr*, expressed higher levels of canonical white fat marker genes *Leptin* (*Lep*) and *Nnat*, and exhibited the lowest expression levels of thermogenic (beige) genes. Two additional white adipocyte clusters were designated as '*de novo* lipogenesis (DNL)-low' and 'DNL-high' cells, both of which expressed lower levels of *Npr3* and shared selective expression of *Fgf14.* DNL-high cells uniquely expressed *Ces1f* and *Gsta3*, and activated high levels of DNL pathway genes (i.e., *Fasn*, *Acss2* and *Acly*) upon cold exposure (***Figure 5F***). Quantification of adipocyte nuclei from this data set showed that the proportions of *Npr3*-high and DNL-high adipocytes remain stable across temperature, with aged mice having more *Npr3*-high adipocytes. The proportion of beige adipocytes increased dramatically during cold exposure selectively in young animals, as expected, while DNL-low adipocytes decreased with cold exposure in both young and aged mice (***Figure 5G***).

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Figure 6

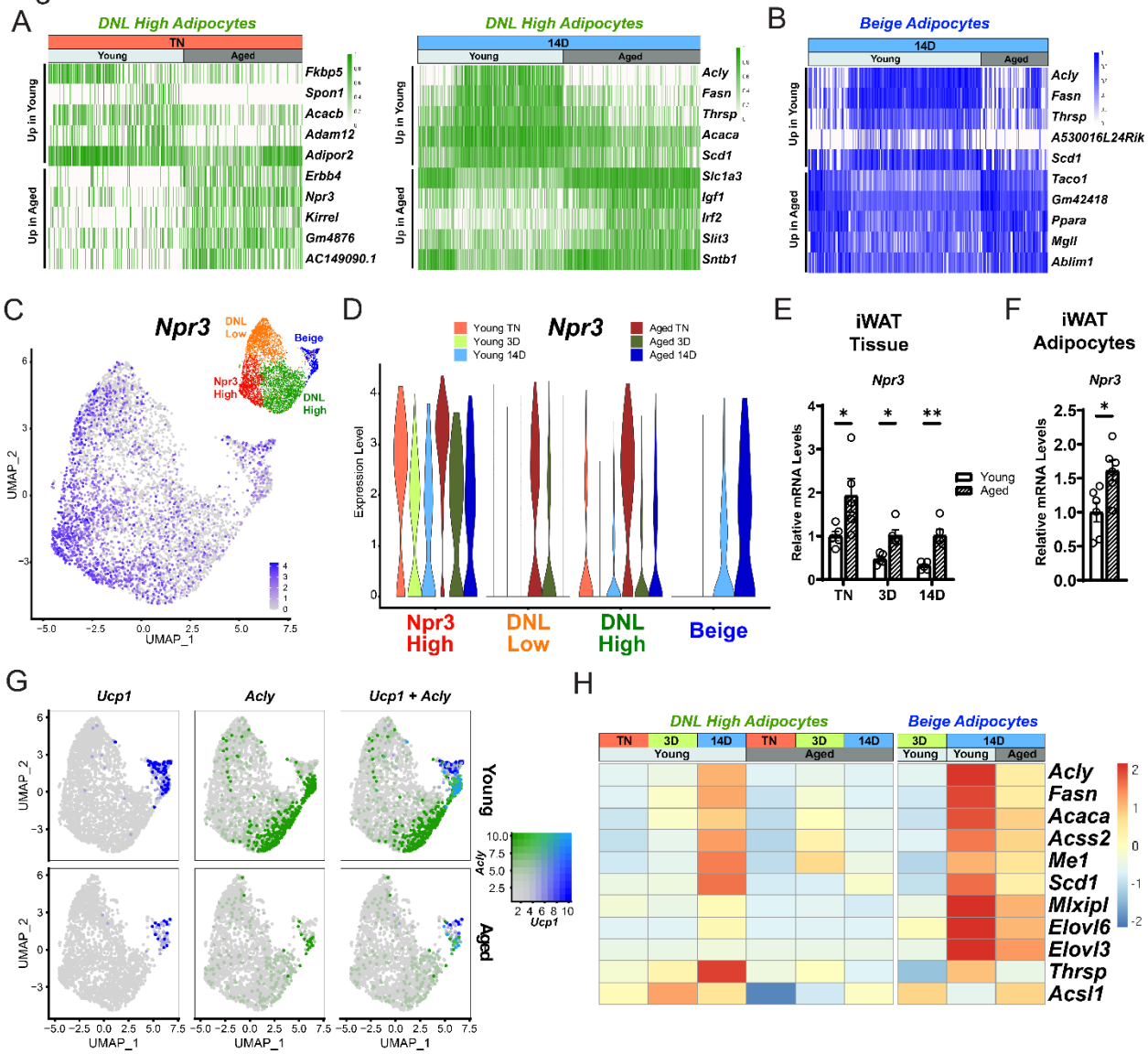

Figure 6. Aging blocks activation of the lipogenic gene program in adipocytes

(**A**) Expression heatmap of the top aging-regulated genes in DNL-high adipocytes at TN (left) and after 14 days of cold exposure (right). (**B**) Expression heatmap of the top aging-regulated genes in beige adipocytes after 14 days of cold exposure. (**C**) UMAP of *Npr3* mRNA levels in adipocyte populations (from Figure 5D). (**D**) Violin plot showing *Npr3* mRNA levels in adipocyte populations, Y-axis = log-scale normalized read count, first bar in beige is 'Young 3D'. (**E**) *Npr3* mRNA levels in iWAT from mouse groups described in Figure 1A, n=5. (**F**) *Npr3* mRNA levels in isolated adipocytes from TN- acclimated young and aged mice, n=6. (**G**) UMAPs of *Ucp1, Acly,* and co-expression mRNA levels in adipocyte populations from all young and aged mice. (**H**) Heatmap showing average expression of lipogenic genes in all nuclei from DNL-high and beige adipocytes per condition indicated in the top table. Data represent mean ± SEM, points represent biological replicates, 2 groups analyzed using a Student's t-test, and multiple conditions analyzed with a Holm-Šidák correction for multiple comparisons. Significance: not significant, P > 0.05; * P < 0.05 ** P < 0.01; *** P < 0.001.

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Aging dysregulates gene programming in adipocyte populations

To evaluate the global effects of cold exposure and aging on adipocytes, we performed differential gene expression analysis between young and aged adipocytes within each cluster. DNL-high and beige adipocytes exhibited the most dramatic expression changes between young and aged animals (***Figures 6A-B, S4B-C***). At TN, DNL-high cells from aged animals expressed lower levels of several genes, including *Fkbp5*, *Spon1* and *Adam12.* Interestingly, *Npr3*, in addition to marking *Npr3*-high cells, was increased by aging in DNL-high adipocytes and to a lesser extent in other adipocyte populations (***Figure 6C,D***). In young animals, *Npr3* expression was downregulated by cold exposure in the three white adipocyte populations, and this downregulation was blunted in aged animals (***Figure 6D***). Gene expression analysis of whole iWAT pads confirmed that *Npr3* mRNA levels are progressively decreased by cold exposure and elevated in aged versus young mice under all temperature conditions (***Figure 6E***). *Npr3* expression levels were also increased in isolated primary adipocytes from aged relative to young mice (***Figure 6F***). Expression levels of the G-protein coupled NP receptors *Npr1* or *Npr2* were not modulated by cold or aging in iWAT or iWAT adipocytes ***(Figure S4D,E)****.*

We also observed a striking activation of the DNL and related gene programs (*Acly*, *Fasn*, *Acaca*, *Scd1*, etc.) in DNL-high and beige adipocytes during cold exposure (***Figures 6G,H***). The induction of these genes during cold exposure, exemplified by *Acly* expression, was a cluster-defining attribute of DNL-high cells, which did not express beige genes like *Ucp1* even after 14 days of cold exposure. Of note, we found two types of beige (UCP1^{+}) adipocytes, distinguished by the presence vs. absence of high DNL gene levels (i.e., UCP1^{+}; DNL^{+} and UCP1^{+};DNL($^{-}$)), with the latter arising first during cold exposure (3D vs. 14D) (***Figures 6G, S4F,G***). Importantly, the induction of DNL genes was nearly completely blocked in DNL-high cells and reduced in beige cells of aged animals (***Figure 6G***). Indeed, the top aging downregulated genes in adipocytes from cold exposed mice correspond to DNL and related pathways, especially in DNL-high cells (***Figure S4I)***. Lastly, at the whole tissue level, we observed robust induction of *Acly* in iWAT of young relative to aged mice with increasing duration of cold exposure (***Figure S4H***). Taken together, these results implicate the suppression of natriuretic peptide signaling and DNL in contributing to the aging-related impairment of beige fat formation.

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Discussion

Thermogenic adipose tissue activity declines during aging of mice and humans, correlating with increases in fat mass and susceptibility to cardiometabolic diseases (Berry et al., 2017; Cypess et al., 2009; Pfannenberg et al., 2010; Rogers et al., 2012; Saito et al., 2009; W. Wang et al., 2019; Yoneshiro et al., 2011). Our study provides a comprehensive unbiased profile of the adipose tissue beiging process and reveals pathways dysregulated by aging in ASPCs and adipocytes during this process.

Beige adipocytes develop via the *de novo* differentiation of ASPCs or through activation of the thermogenic gene program in mature adipocytes. Previous studies defined three populations of fibroblastic ASPCs in iWAT, namely *Dpp4*$^+$ interstitial cells, *Icam1*$^+$ preadipocytes, and *Cd142*$^+$ cells (Burl et al., 2018; Merrick et al., 2019). Aging or cold exposure did not induce dramatic shifts in either the proportions, or gene expression signatures of any of these ASPC types, suggesting that these cell populations are stably maintained across a range of conditions. In support of this, aging did not diminish the cell-intrinsic adipogenic capacities of these ASPC populations, when isolated and subjected to adipogenesis assays *ex vivo*. Notably, we did not observe the emergence of aging-dependent regulatory cells (ARCs), previously described as modulated ASPCs co-expressing ASPC and immune marker genes, which have the capacity to suppress adipocyte differentiation (Nguyen et al., 2021). However, we did observe the induction of ARC-selective gene markers (i.e., *Lgals3*, *Cd36*) specifically in immune cells (*Ptprc*$^+$, *Adgre1*$^+$) from aged mice in both our scRNA-seq and snRNA-seq datasets. This *Lgals3*/*Cd36* gene signature has also been described in Lin$^+$ macrophages and CD45$^+$ lipid-associated (LAM) macrophages (Burl et al., 2018; Jaitin et al., 2019). Overall, our results suggest that aging-induced alterations to the systemic milieu or adipose tissue environment are responsible for the block in beige adipogenesis.

Gene expression analyses identified several genes that were altered by aging across multiple ASPC types and temperature conditions. The top aging-upregulated gene was *Cd9*, which was previously identified as a marker of fibrogenic (fibrosis-generating) progenitor cells (Marcelin et al., 2017). *Cd9* encodes for a tetraspanin protein implicated in various processes that could affect adipogenesis, including extracellular vesicle production, cell adhesion, inflammation, and platelet activation (Brosseau, Colas, Magnan, & Brouard, 2018). Aging also upregulated the expression of *Pltp* and *Gpnmb*, which are both linked to the regulation of inflammation and fibrosis (Prabata, Ikeda, Rahardini, Hirata, & Emoto, 2021; Saade, Araujo de Souza, Scavone, & Kinoshita, 2021). Conversely, *Meg3*, *Itm2a* and *Postn* were consistently downregulated across all ASPC populations from aged versus young mice. Of note, Periostin (*Postn*) is an extracellular

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matrix protein that regulates adipose tissue lipid storage, and its levels were previously shown to decrease in several adipose tissue depots during aging (Graja et al., 2018).

We were surprised by the limited (<20%) contribution of fibroblastic (*Pdgfra*$^{+}$) ASPCs, (which includes *Pparg*-expressing preadipocytes), to beige adipocytes during cold exposure. Previous studies in mice using an adipocyte fate tracking system show that a high proportion of beige adipocytes arise via the *de novo* differentiation of ASPCs (Q. A. Wang, Tao, Gupta, & Scherer, 2013). However, the relative contribution from ASPC differentiation and direct adipocyte conversion to the formation of beige adipocytes depends highly on the experimental conditions, especially cold exposure history (Shao et al., 2019). Mice housed at TN from birth undergo high rates of *de novo* beige adipogenesis upon first cold exposure, whereas mice reared at room temperature acquire many 'dormant' beige adipocytes that can be re-activated by cold exposure (Rosenwald, Perdikari, Rulicke, & Wolfrum, 2013; Shao et al., 2019). Based on these findings, we presume that mature (dormant beige) adipocytes serve as the major source of beige adipocytes in our cold-exposure paradigm. However, long-term cold exposure also recruits smooth muscle cells to differentiate into beige adipocytes; a process that we did not investigate here (Berry, Jiang, & Graff, 2016; Long et al., 2014; McDonald et al., 2015; Shamsi et al., 2021).

The beiging process is associated with a dramatic remodeling of adipose tissue structure and metabolic function. We applied snRNA-seq analysis to investigate the cold response of iWAT adipocytes in young and aged animals, leading us to identify four adipocyte clusters: beige adipocytes and three "white" subsets: *Npr3*-high, DNL-low and DNL-high adipocytes. *Npr3*-high adipocytes were enriched for expression of white fat-selective genes and exhibit the lowest levels of thermogenic genes (Rosell et al., 2014; Ussar et al., 2014). Interestingly, *Npr3* also upregulated by aging in all white adipocytes. Previous studies show that obesity also increases *Npr3* levels in adipose tissue of mice and humans (Gentili et al., 2017; Kovacova et al., 2016). NPR3 represses beige fat development and adipocyte thermogenesis by functioning as a clearance receptor for natriuretic peptides (NPs), thereby reducing their lipolytic and thermogenic effects (Bordicchia et al., 2012; Coue et al., 2018; Moro et al., 2004; Sengenès, Berlan, Glisezinski, Lafontan, & Galitzky, 2000; Sengenes et al., 2003). Together, these results suggest that *Npr3*-high adipocytes may impede beige fat development in a cell non-autonomous manner by reducing NP signaling. Moreover, high NPR3 levels in aged animals could contribute to the block in beige fat development, and targeting this pathway may be a promising avenue to elevate beige fat activity.

We were also intrigued by the dramatic induction of lipogenesis genes in both beige adipocytes and DNL-high cells during cold exposure. Previous work established that cold stimulates opposing pathways of lipid oxidation and lipogenesis in thermogenic fat tissue (Mottillo

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et al., 2014; Sanchez-Gurmaches et al., 2018; Yu, Lewin, Forrest, & Adams, 2002). The co-occurrence of these two processes is unusual and may provide a mechanism to ensure the continued availability of fatty acids to fuel thermogenesis and/or provide critical metabolic intermediates, such as acetyl-CoA. The Granneman lab demonstrated that high expression of the lipid catabolic enzyme MCAD and lipogenic enzyme FAS occurred in separate populations of iWAT adipocytes upon stimulation with a β3-adrenergic agonist for 3-7 days (Lee, Kim, Kwon, & Granneman, 2017). We identified two subsets of UCP1^{+} beige adipocytes, distinguished by the presence vs. absence of high levels of DNL genes (i.e., UCP1^{+}; DNL-high and UCP1^{+}; DNL-low). Interestingly, the UCP1^{+}; DNL-high cells accumulated later during cold exposure (14D), suggesting that fully cold-adapted beige adipocytes express both pathways simultaneously. Of note, the induction of *Acly* and other lipogenic genes was very severely impaired in aged animals. Related to this point, Martinez Calejman and colleagues showed that *Acly* deficiency in brown adipocytes caused a whitened phenotype, coupled with an unexpected and unexplained reduction in *Ucp1* expression (Martinez Calejman et al., 2020). We speculate that high levels of ACLY may be required to support thermogenic gene transcription by supplying and efficiently shuttling acetyl-CoA for acetylation of histones or other factors.

In summary, this work shows that aging impairs beige adipogenesis through non-cell-autonomous effects on adipose tissue precursors and by disrupting adipocyte responses to environmental cold exposure. Expression profiling at the single-cell level reveals adipocyte heterogeneity, including two different types of UCP1^{+} beige adipocytes. Finally, aging-dysregulated pathways, including natriuretic peptide signaling and lipogenesis, may provide promising targets for unlocking beige adipocyte development.

Acknowledgements

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Author Contributions: C.D.H, A.P.S, R.C. and P.S. were responsible for conceptualization and data analysis. C.D.H and P.S were responsible for writing of the manuscript. C.D.H and A.P.S conducted the majority of the experiments. R.C. and E.F. performed bioinformatics analyses. L.C. processed tissue sections for histology and performed immunostaining. C.J., L.T., and E.D.R. performed and processed the snRNA-seq experiment.

Competing Interests: The authors declare no competing interests.

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Data and materials availability: scRNA-seq and snRNA-seq datasets are deposited in the Gene Expression Omnibus (GEO) under the super series accession number GSE227441. Data analysis pipelines used for processing of raw sequencing data, integration and clustering can be obtained from: https://github.com/calhounr/Aging-impairs-cold-induced-beige-adipogenesis-and-adipocyte-metabolic-reprogramming

Supplemental Figures

Figure S1

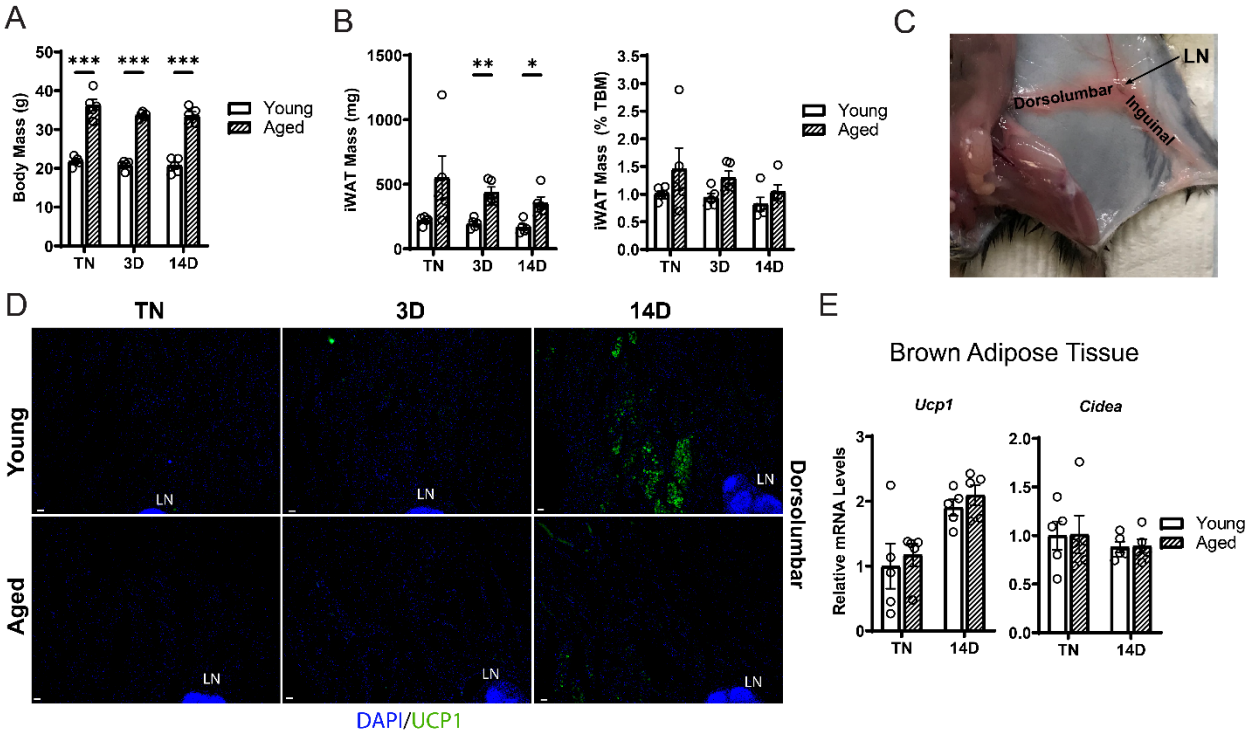

Figure S1, related to Figure 1. (**A-B**) Body mass and iWAT mass of mice described in Figure 1A, n=5. (**C**) Mouse dissection with lymph node (LN) orientation showing the dorsolumbar and inguinal regions of the iWAT pad. (**D**) Immunofluorescence analysis of iWAT with UCP1 (green) and DAPI (blue). LN=lymph node. Scale bar 100 µm. (**E**) mRNA levels of *Ucp1* and *Cidea* in BAT of young and aged mice housed at TN, and either maintained at TN or exposed to cold for 2 weeks. Data represent mean ± SEM, points represent biological replicates, analyzed using a Student's t-test with a Holm-Šidák correction for multiple comparisons. Significance: not significant, P > 0.05; * P < 0.05 ** P < 0.01; *** P < 0.001.

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Figure S2

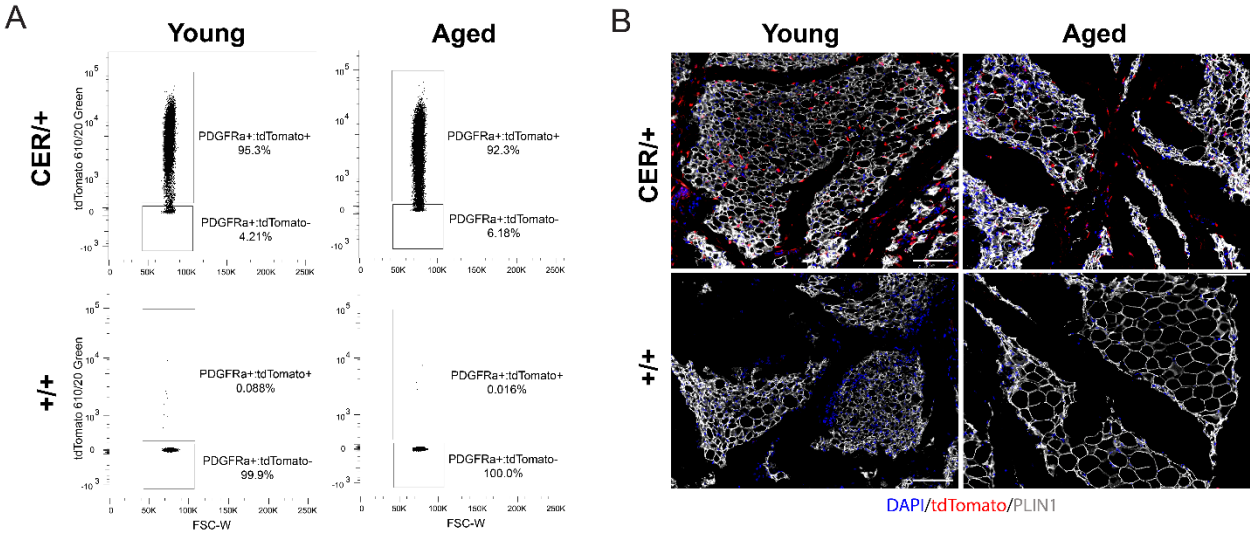

Figure S2, related to Figure 2. (**A**) Representative flow cytometry plots showing expression of tdTomato in gated Live, Lin$^-$; PDGFRα$^+$ stromal vascular cells isolated from young and aged reporter mice (described in Figure 2) immediately after treatment with tamoxifen (tmx, pulse). (**B**) Immunofluorescence analysis of iWAT from young and aged reporter mice with tdTomato (red), PLIN1 (white) and DAPI (blue) after the tmx pulse, scale bar 100 µm.

Figure S3

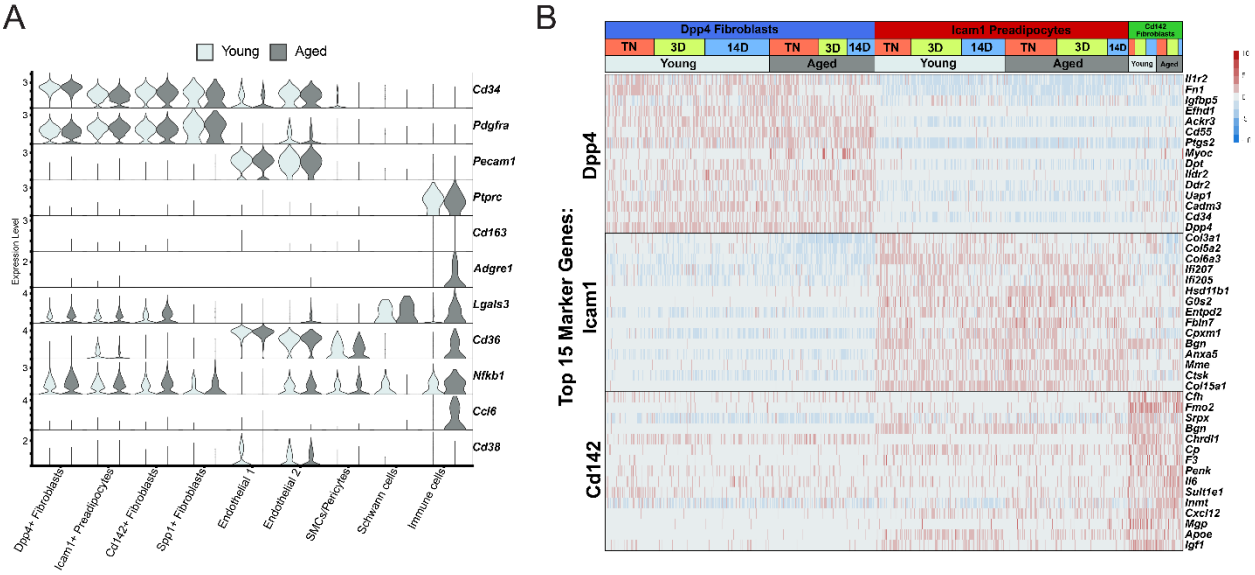

Figure S3, related to Figure 3. (**A**) Violin plot showing expression of ARC marker genes in cell clusters split by age, Y-axis = log-scale normalized read count. (**B**) Expression heatmap of top ASPC marker genes across age and housing conditions.

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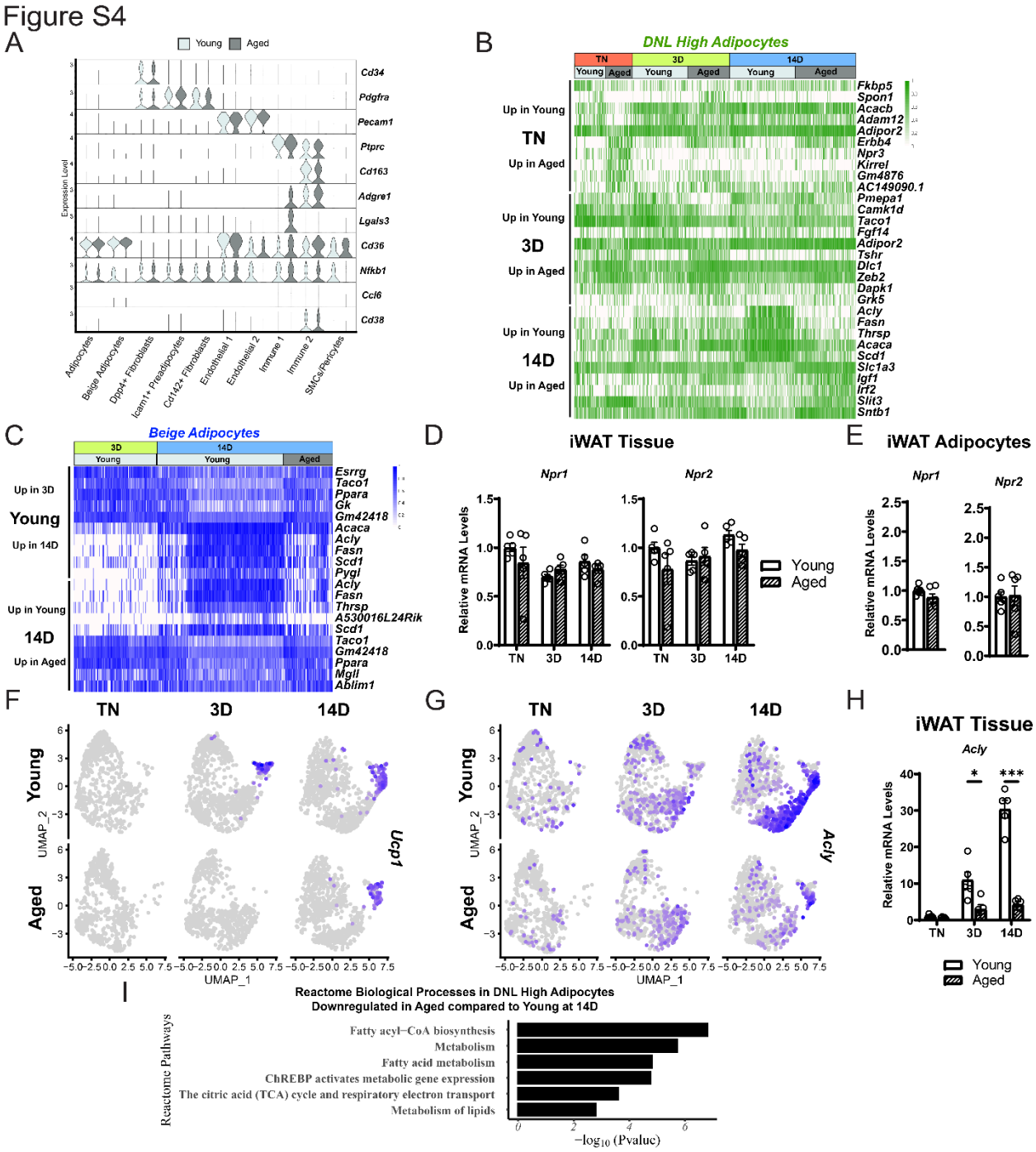

Figure S4, related to Figures 5,6. (**A**) Violin plot showing expression levels of ARC marker genes split by age, y-axis = log-scale normalized read count. (**B**) Expression heatmap of the top aging-regulated genes in DNL-high adipocytes. (**C**) Expression heatmap of the top aging-regulated and cold-regulated genes in beige adipocytes. (**D-E**) *Npr1* and *Npr2* mRNA levels in (D) iWAT from mouse groups described in Figure 1A, n=5 and (E) isolated adipocytes from iWAT from TN-acclimated young and aged mice, n=6. (**E-F**) UMAP of *Ucp1* (E) and *Acly* (F) mRNA levels in adipocyte populations (from Figure 5D). (**H**) *Acly* mRNA levels in iWAT from mouse groups described in Figure 1A, n=5. (**G**) Enrichment analysis displaying the top six Reactome pathways in DNL high adipocytes downregulated in aged at 14 days. Data represent mean ± SEM, points represent

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biological replicates, 2 groups analyzed using a Student's t-test, and multiple conditions analyzed with a Holm-Šidák correction for multiple comparisons. Significance: not significant, P > 0.05; * P < 0.05 ** P < 0.01; *** P < 0.001.

Materials and Methods

Key Resources Table

Reagent type (species) or resource	Designation	Source or reference	Identifiers	Additional information
genetic reagent (M. *musculus*)	C57BL/6J	The Jackson Laboratory, Bar Harbor, ME	RRID:IMSR_JAX:000664	
genetic reagent (M. *musculus*)	C57BL/6JN	NIA, Bethesda, MD	NA	
genetic reagent (M. *musculus*)	Rosa26 loxp-stop-loxp tdTomato Reporter (Ai14)	The Jackson Laboratory, Bar Harbor, ME	RRID:IMSR_JAX:007914	
genetic reagent (M. *musculus*)	Pdgfra^{CreERT2}	The Jackson Laboratory, Bar Harbor, ME	RRID:IMSR_JAX:032770	
antibody	Rabbit anti–red fluorescent protein (RFP)	Rockland, Pottstown, PA	600-401-379, RRID:AB_2209751	1:500
antibody	Rabbit anti-Perilipin (D418)	Cell Signaling, Denvers, MA	3470, RRID:AB_2167268	1:200
antibody	Rabbit anti- UCP1	Specially made by AstraZeneca, Cambridge, UK	NA	1:2000
antibody	Anti-mouse CD142	Sino Biological, Chesterbrook, PA	50413- R001	1:100
antibody	Anti-mouse CD142	R & D Systems, Minneapolis, MN	AF3178, RRID:AB_2278143	1:50
antibody	Anti-mouse CD140a-(PDGFRα)-PECy7	Biolegend, San Diego, CA	135912, RRID:AB_2715974	1:100
antibody	Anti-mouse-CD31 (APC-Fire)	Biolegend, San Diego, CA	102528, RRID:AB_2721491	1:1000
antibody	Anti-mouse CD45-allophycocyanin (APC/Cy7)	Biolegend, San Diego, CA	103116, RRID:AB_312981	1:1000
antibody	Anti-mouse ICAM1-phycoerythrin (PE/Cy7)	Biolegend, San Diego, CA	116122, RRID:AB_2715950	1:100
antibody	Anti-mouse CD26 (DPP-4)-fluorescein isothiocyanate (FITC)	Biolegend, San Diego, CA	137806, RRID:AB_10663402	1:200
sequence-based reagent	mTbp	PMID: 24703692	NA	F-GAAGCTGCGGTACAATTCCAG R-CCCCTTGTACCCTTCACCAAT
sequence-based reagent	mAdipoq	PMID: 24703692	NA	F-GCACTGGCAAGTTCTACTGCAA R-GTAGGTGAAGAGAACGGCCTTGT
sequence-based reagent	mFabp4	PMID: 24703692	NA	F-ACACCGAGATTTCCTTCAAACTG R-CCATCTAGGGTTATGATGCTCTTCA

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sequence-based reagent	mCidea	PMID: 24703692	NA	F-TGCTCTTCTGTATCGCCCAGT R-GCCGTGTTAAGGAATCTGCTG
sequence-based reagent	mPgc1a	PMID: 24703692	NA	F-CCCTGCCATTGTTAAGACC R-TGCTGCTGTTCCTGTTTTC
sequence-based reagent	mUcp1	PMID: 24703692	NA	F-ACTGCCACACCTCCAGTCATT R-CTTTGCCTCACTCAGGATTGG
sequence-based reagent	mDio2	PMID: 24703692	NA	F-CAGTGTGGTGCACGTCTCCAATC R-TGAACCAAAGTTGACCACCAG
sequence-based reagent	mAcly	PMID: 31141698	NA	F-GAGTGCTATTGCGCTTCCC R-GGTTGCCGAAGTCACAGGT
sequence-based reagent	mNpr3	This Paper	NA	F-TTTTCAGGAGGAGGGGTTGC R-ACACATGATCACCACTCGCT
sequence-based reagent	mNpr1	MGH PrimerBank	Primer Bank ID: 113930717c1	F-GCTTGTGCTCTATGCAGATCG R-CCTCGACGAACTCCTGGTG
sequence-based reagent	mNpr2	MGH PrimerBank	Primer Bank ID: 118129825c2	F-CATGACCCCGACCTTCTGTTG R-CGAACCAGGGTACGATAATGCT
commercial assay or kit	ABI High-Capacity cDNA Synthesis kit	Applied Biosystems, Waltham, MA	4368813	
commercial assay or kit	Purelink RNA Mini columns	Invitrogen, Waltham, MA	LT-12183018	
commercial assay or kit	TSA TMR Tyramide Reagent Pack	Akoya Biosciences, Marlborough, MA	NEL742001KT	
commercial assay or kit	TSA Fluorescein Tyramide Reagent Pack	Akoya Biosciences, Marlborough, MA	NEL741001KT	
commercial assay or kit	Bulls Eye Decloaking Buffer	Biocare, Pacheco, CA	BULL1000 MX	
commercial assay or kit	AbC Total Antibody Compensation Bead Kit	BioLegend,San Diego, CA	A10497	
commercial assay or kit	Biotium Mix-n-Stain CF647	Sigma, Burlington, MA	MX647S100	
commercial assay or kit	PicoPure RNA Isolation Kit	Invitrogen, Waltham, MA	KIT0204	
commercial assay or kit	Qubit dsDNA High Sensitivity assay kit	ThermoFisher, Waltham, MA	Q32851	
commercial assay or kit	DNA High Sensitivity Bioanalyzer Chip (Agilent)	Agilent, Santa Clara, CA	5067-4626	
software, algorithm	Graphpad Prism	Graphpad, San Diego, CA	RRID:SCR_002798	
software, algorithm	Adobe Illustrator	Adobe, San Jose, CA	RRID:SCR_010279	
software, algorithm	Adobe Photoshop	Adobe, San Jose, CA	RRID:SCR_014199	
software, algorithm	Image J	PMID: 22743772	RRID:SCR_003070	
software, algorithm	Cell Ranger	10x Genomics	RRID:SCR_017344	
software, algorithm	Seurat	PMID: 34062119	RRID:SCR_016341	
software, algorithm	bcl2fastq	Illumina	RRID:SCR_015058	
software, algorithm	Cumulus	PMID: 32719530	RRID:SCR_021644	

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software, algorithm	FACSDiva Softward	Becton Dickinson, Franklin Lakes, NJ	RRID:SCR_001456	
other	Tamoxifen (Free Base)	Sigma, Burlington, MA	T5648	
other	Corn Oil	Sigma, Burlington, MA	C8267	
other	16% Paraformaldehyde	EMS, Hatfield, PA	15710	
other	TRIzol	Invitrogen, Waltham, MA	15596018	
other	CL-316,243	Sigma, Burlington, MA	C5976	
other	4',6-Diamidine-2'-phenylindole dihydrochloride (DAPI), 1:10,000	Roche, Basel, Switzerland	10236276001	
other	Bovine Serum Albumin, fraction V, fatty-acid free	Gold Biotechnology, St. Louis, MO	A-421-250	
other	DMEM/F12	Fisher Scientific, Waltham, MA	11320033	
other	Fetal Bovine Serum	Omega Scientific, Tarzana, CA	FB-11, Lot 401714	
other	Primocin	InvivoGen, San Diego, CA	ant-pm-2	
other	PCR Master Mix, Power SYBR Green	Applied Biosystems, Waltham, MA	4367659	
other	HBSS, 1X	Fisher Scientific, Waltham, MA	14175079	
other	Dispase II	Roche, Basel, Switzerland	4942078001	
other	Collagenase, Type 1	Worthington, Lakewood, NJ	LS004197	
other	Red Blood Cell Lysis Buffer, 10x	BioLegend, San Diego, CA	420302	
other	Human Insulin, Novolin	Novo Nordisk, Bagsvaerd, Denmark	183311	
other	Dexamethasone	Sigma-Aldrich, Burlington, VT	D4902	
other	3-isobutyl-1-methylxanthine (IBMX)	Sigma-Aldrich, Burlington, VT	I7018	
other	Rosiglitazone	Cayman Chemical, Ann Arbor, MI	11884	
other	Indomethacin	Sigma-Aldrich, Burlington, VT	I8280	
other	3,30,5-Triiodo-L-thyronine sodium salt (T3)	Sigma-Aldrich, Burlington, VT	T6397	
other	isoproterenol	Sigma-Aldrich, Burlington, VT	I6504	
other	Biodipy 493/503	Invitrogen, Waltham, MA	D3922	
other	Hoechst 33342	Thermo Fisher, Waltham, MA	62249	
other	Protector RNase Inhibitor	Roche, Basel, Switzerland	3335399001	

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Mice

All animal procedures were approved and performed under the guidance of the University of Pennsylvania Institutional Animal Care and Use Committee. Young (4 weeks) and aged (52 weeks) C57BL/6 male mice were obtained from the National Institute of Aging (C57BL/6JN) or Jackson Laboratories (C57BL/6J, stock number 000664). Mice were housed at 30°C for 3 weeks, then were either: maintained at 30°C for 2 weeks (TN); kept at 30°C for 11 more days before moving to 6°C for 3 days (3D cold) or moved to 6°C for 14 days (14D cold). Mice were single housed during the final two week temperature treatment and provided with a nestlet and shepherd shack. For experiments with CL316,243 (CL, Sigma-C5976), mice were housed at 30°C for 5 weeks, followed by intraperitoneal (IP) injection of 1 mg/kg/d CL either 1 hour prior to tissue harvest or for 5 days. *Pdgfra*^{CreERT2} mice were obtained from Dr. Brigid Hogan (Duke University) (Chung, Bujnis, Barkauskas, Kobayashi, & Hogan, 2018) and crossed with *Rosa26*^{tdTomato} (strain: B6.Cg-Gt(ROSA)26Sortm14(CAG-tdTomato)Hze/J, stock no. 007914). To induce Cre activity, tamoxifen (Sigma, T5648) dissolved in corn oil (Sigma, C8267) was injected intraperitonially (IP) into mice at a dose of 100 mg/kg/d for 5 days. For all iWAT processing other than histology, the inguinal lymph node was removed.

Histology and Immunofluorescence

Tissues were fixed overnight in 4% paraformaldehyde, washed with PBS, dehydrated in ethanol, paraffin-embedded and sectioned. Following deparaffinization, slides were subjected to heat antigen retrieval in a pressure cooker with Bulls Eye Decloaking buffer (Biocare), unless otherwise noted. Slides were incubated in primary antibody overnight and secondary antibody conjugated to peroxidase and then developed using Tyramide Signal Amplification (TSA, Akoya Biosciences). Samples were stained with the following antibodies: anti-red fluorescent protein (RFP) (rabbit; 1:500; Rockland #600-401-379), anti-UCP1 (rabbit, 1:2000, AstraZeneca), and anti-PLIN1 (rabbit, 1:200 Cell Signaling #3470). Slides were imaged on an inverted fluorescence microscope (Keyence BZ-X710). For quantification of tdTomato-expressing adipocytes, full-length iWAT slices were tile imaged, stitched, exported as a BigTiff, and quantified using the Count Tool in Photoshop (Adobe).

Isolation of stromal vascular cells (SCVs) and adipocytes

SVCs. As previously described (Merrick et al 2019, Wang et al 2019), iWAT tissue was dissected, minced gently and digested with Collagenase Type I (1.5 units/ml; Worthington) and Dispase II (2.4 units/ml; Roche) in DMEM/F12 containing 1% fatty acid-free bovine serum albumin (Gold

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Biotechnology) in a gentleMACS dissociator (Miltenyi Biotec) on program "37 MR ATDK-1." The digestion was quenched with DMEM/F12 containing 10% FBS, and the dissociated cells were passed through a 100 µm filter and spun at 400 x g for 4 mins. The pellet was resuspended in red blood cell lysis buffer (BioLegend), incubated for 4 mins at RT, then quenched with DMEM/F12 containing 10% serum. Cells were passed through a 70 µm filter, spun, resuspended, then passed through a final 40 µm filter, spun at 400 x g for 4 minutes and plated or underwent further processing for FACS. Mice were not pooled unless indicated.

Adipocytes. Tissue went through the same process as above, except after digestion and quenching, adipocyte/SVF slurry was filtered through a 200 µm filter and centrifuged at 50 x g for 3 mins at RT. Using a 20 mL syringe and 1.5-inch, 25G needle, media containing the SVCs was removed from below the adipocytes (and saved if concurrently isolating SVCs), leaving only the adipocytes in the tube. Adipocytes were washed twice with the same media as quenching, transferred to 2 mL tubes, spun a final time, media was removed from below the adipocytes again, and TRIzol was added for RNA extraction. Mice were not pooled.

FACS

DPP4$^+$, ICAM1$^+$, and CD142$^+$ cells were isolated as previously described (Merrick et al 2019). Briefly, SVCs from the subcutaneous adipose of mice (n= 2-5) were pooled and resuspended in FACS buffer (HBSS containing 3% FBS; Fisher), then incubated for 1 hr at 4°C with the following antibodies: CD26 (DPP4)-fluorescein isothiocyanate (FITC) (Biolegend, 137806; 1:200), anti-mouse ICAM1-phycoerythrin (PE)/Cy7 (Biolegend, 116122; 1:100), anti-mouse CD45-allophycocyanin (APC)/Cy7 (Biolegend, 103116; 1:1000), anti-mouse CD31-APC-Fire (Biolegend, 102528; 1:1000), and anti-mouse CD142 (Sino Biological, 50413-R001, 1:100; or R&D Systems, AF3178, 1:50). Anti-mouse CD142 antibodies were conjugated with Biotium Mix-n-Stain CF647 (Sigma, MX647S100). For lineage tracing pulse analysis, SVCs were isolated from individual mice without pooling. SVCs were stained with anti-mouse CD31, anti-mouse CD45, and anti-mouse CD140a (PDGFRA) (PE/Cy7) (Biolegend, 135912; 1:100). In all FACS experiments, cells were stained with 4′,6-diamidino-2-phenylindole (DAPI) (Roche, 10236276001; 1:10,000) for 5 minutes, then washed three times with FACS buffer to remove unbound antibodies. Cells were sorted with a BD FACS Aria cell sorter (BD Biosciences) equipped with a 100 µm nozzle and the following lasers and filters: DAPI, 405 and 450/50 nm; FITC, 488 and 515/20 nm; mTomato, 532 and 610/20 nm; PE/Cy7, 532 and 780/60 nm; CF647, 640 and 660/20 nm; and APC/Cy7 and APC-Fire, 640 and 780/60 nm. All compensation was performed at the

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time of acquisition in Diva software by using compensation beads (BioLegend, A10497) for single-color staining and SVCs for negative staining and fluorescence (DAPI and tdTomato).

Cell culture and differentiation

Adipocyte precursor cells. All cells were cultured in DMEM/F12 containing 10% FBS and Primocin (50 ng/ml) (InvivoGen, ant-pm-1). DPP4$^+$, ICAM1$^+$, and CD142$^+$ populations were FACS purified, plated on CellBind 384-well plates (Corning) at 15-25K cells/well, and incubated for 48 (25K cells) to 72 hours (15K cells) to facilitate attachment before the induction of adipogenic differentiation. For whole SVF, SVCs were isolated and plated in a 48 well CellBind plate (Corning) at a high confluency of one mouse per 18 wells. No cells were passaged after plating to maintain adipogenic competency. Differentiation was carried out with either maximum adipogenic cocktail, max: 500 μM isobutylmethylxanthine (Sigma, I7018), 10 μM dexamethasone (Sigma, D4902), 125 μM indomethacin (Sigma, I8280), 1 μM rosiglitazone (Cayman Chemical, 11884), 1 nM T3 (Sigma, T6397), and 20 nM insulin (Novolin) or a minimal adipogenic cocktail, min: 20 nM insulin. For the max adipogenic cocktail induction, cells were incubated with cocktail for 2 days and then transferred to adipogenic maintenance medium for the remaining 6 days (1 μM rosiglitazone, 1 nM T3, and 20 nM insulin). For all conditions, medium was changed every 2 days, and cells were harvested on day 8 of differentiation. For drug treatments, cells were treated for 4 hrs on day 8 with 1 μM isoproterenol (Sigma, I6504). Adipogenesis was assessed by staining with Biodipy 493/503 (Invitrogen, D3922) for lipid droplet accumulation and Hoechst 33342 (Thermo Fisher, 62249) for nuclei number. The cells were imaged on a Keyence inverted fluorescence microscope (BZ-X710) by using DAPI (excitation, 360/40 nm; emission, 460/50 nm) and green fluorescent protein (excitation, 470/40 nm; emission, 525/50 nm) filters. Individual wells were imaged in their entirety at 4x magnification, and at 20x to see morphology. 384-well plates were not stained and imaged in brightfield due to low cell number recovery from FACS prior to RNA extraction.

RNA Extraction, qRT-PCR and RNA Sequencing

RNA Extraction. Total RNA was extracted using TRIzol (Invitrogen) combined with PureLink RNA Mini columns (Thermo Fisher, 12183025) for tissue and SVC cells or by PicoPure RNA Isolation Kit (Applied Biosystems, KIT0204) for 384-well plate populations and adipocytes. Prior to the addition of chloroform, all tissue and primary adipocytes in TRIzol included an extra spin at max speed for 10 minutes at RT, then TRIzol was removed from below the lipid layer to avoid lipid contamination disrupting the subsequent phase separation with chloroform. Chloroform was added to the lipid-free TRIzol, spun for 15 mins at 12,000 x g and the aqueous layer was removed

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and added to columns. mRNA was quantified using a Nanodrop and reverse transcribed to cDNA using the ABI High-Capacity cDNA Synthesis kit (ABI, 4368813). Real-time PCR was performed on a QuantStudio5 qPCR machine using SYBR green fluorescent dye (Applied Biosystems). Fold changes were calculated using the ddCT method, with TATA binding Protein (*Tbp*) mRNA serving as a normalization control.

Single Cell RNA-seq Samples. Cells were flow sorted to isolate live ($DAPI^-$) cells and remove debris. We enriched non-immune cells by sorting out $CD45^+$ cells. Next-generation sequencing libraries were prepared using the Chromium Next GEM Single Cell 3' Reagent kit v3.1 (10x Genomics, 1000121) per manufacturer's instructions. Libraries were uniquely indexed using the Chromium Single Index Kit T Set A, pooled, and sequenced on an Illumina NovaSeq 6000 sequencer in a paired-end, dual indexing run by the CHOP Center for Applied Genomics at the University of Pennsylvania. Sequencing for each library targeted 20,000 mean reads per cell.

Single Nucleus RNA-seq Samples.

Nuclei were isolated from frozen mouse iWAT samples as previously described, with the following modifications to integrate hash multiplexing and FANS-assisted nuclear quality thresholding and sample pooling (Drokhlyansky et al., 2020; Slyper et al., 2020). Briefly, 300 mg of flash-frozen adipose samples were held on dry ice until immediately before nuclei isolation, and all sample handling steps were performed on ice. Each sample was placed into a gentleMACS C tube (Miltenyi Biotec, 130-093-237) with 2 mL freshly prepared TST buffer (0.03% Tween 20 (Bio-Rad), 0.01% Molecular Grade BSA (New England Biolabs), 146 mM NaCl (ThermoFisher Scientific), 1 mM $CaCl_2$ (VWR International), 21 mM $MgCl_2$ (Sigma Aldrich), and 10 mM Tris-HCl pH 7.5 (ThermoFisher Scientific) in ultrapure water (ThermoFisher Scientific)) with 0.2 U/µL of Protector RNase Inhibitor (Sigma Aldrich, RNAINH-RO). gentleMACS C tubes were then placed on the gentleMACS Dissociator (Miltenyi Biotec) and tissue was dissociated by running the program "mr_adipose_01" three times, and then incubated on ice for 10 minutes. Lysate was passed through a 40 µm nylon filter (CellTreat) and collected into a 50 mL conical tube (Corning). Filter was rinsed with 3 mL of freshly prepared ST buffer (146 mM NaCl, 1 mM $CaCl_2$, 21 mM $MgCl_2$; 10 mM Tris-HCl pH 7.5) with 0.2 U/µL RNase Inhibitor, and collected into the same tube. Flow-through was passed through a 20 µm pre-separation filter (Miltenyi Biotec) set on top of a 5 mL FACS tube (Corning) and collected into the same tube. Suspension was centrifuged in a swinging-bucket centrifuge (Eppendorf) at 500 × g for 5 minutes at 4°C with brake set to low. Following centrifugation, supernatant was removed and 5 mL of PBS pH 7.4 (ThermoFisher Scientific) with

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0.02% BSA and 0.2 U/µL RNase Inhibitor was added without resuspending the nuclear pellet. Sample was centrifuged again at 500 × g for 5 minutes at 4°C with brake set to low. Following centrifugation, supernatant was removed, and the nuclear pellet was resuspended in 1 mL PBS-0.02% BSA with 0.2 U/µL RNase Inhibitor. Each sample was split into two 500 µL aliquots and transferred to new 5 mL FACS tubes for subsequent hashing. Each aliquot of resuspended nuclei was stained with NucBlue (ThermoFisher, R37605), labeled with 1 µg of a unique TotalSeq anti-Nuclear Pore Complex Proteins Hashtag Antibody (Biolegend), and then incubated on ice for 30 minutes. Suspension was centrifuged at 500 × g for 5 minutes at 4°C with brake set to low. Following centrifugation, 450 µL of supernatant was removed and the nuclear pellet was resuspended in 450 µL PBS-0.02% BSA with 0.2 U/µL RNase Inhibitor. For nuclear quality thresholding, fluorescence-activated nuclear sorting (FANS) was implemented to collect 4,000-4,300 nuclei from hashtagged aliquots directly into a shared well of a 96-well PCR plate (Thermo Scientific) containing 24.6 µL of 10X RT Reagent B with 1U/uL RNase Inhibitor on a Beckman Coulter MoFlo AstriosEQ fitted with a 70 µm nozzle. High-quality nuclei were selected by initial gating at 360 nm with laser filter 405-448/59 followed by SSC-H and FSC-H to remove doublets and unlysed cells. Once all sample aliquots were FANS-sorted, the pool of 43,000 nuclei was loaded on the 10x Chromium controller (10x Genomics) according to the manufacturer's protocol. cDNA and gene expression libraries were generated according to the manufacturer's instructions (10x Genomics). Libraries of hashtag oligo fractions were generated according to the manufacturer's instructions (Biolegend). cDNA and gene expression library fragment sizes were assessed with a DNA High Sensitivity Bioanalyzer Chip (Agilent). cDNA and gene expression libraries were quantified using the Qubit dsDNA High Sensitivity assay kit (ThermoFisher, Q32854). Gene expression libraries were multiplexed and sequenced on the Nextseq 500 (Illumina) using a 75-cycle kit and the following read structure: Read 1: 28 cycles, Read 2: 55 cycles, Index Read 1: 8 cycles.

Bioinformatics analysis

Single Cell RNA Sequencing

Data was processed using the Cell Ranger pipeline (10x Genomics, v.3.1.0) for demultiplexing and alignment of sequencing reads to the mm10 transcriptome and creation of feature-barcode matrices. The cell ranger output files were read into R (version 4.1.1) and processed utilizing the standard Seurat CCA integrated workflow (version 4.3.0). Each of the six samples went through a first phase of filtering, where only cells that recorded more than 200 features and only features present in a minimum of 3 cells were kept. Each sample was filtered prior to downstream analysis

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on nCount_RNA, nFeature_RNA, and mitochondrial percentages. Samples were then normalized using a LogNormalization method with a scaling factor of 10000 followed by FindVariableFeatures using Variance Stabilization Transformation with the top 6000 features to be returned. The samples were scored on their cell cycle phases which would be used in the regression later. The FindIntegrationAnchors function using the CCA reduction method and IntegrateData was utilized to integrate the data together. The integrated data-set was then scaled in which mitochondrial percentage and cell cycle state was regressed out. A principal component analysis was performed and the top 15 dimensions were kept. Uniform Manifold and Projection (UMAP) was run on the dataset, in addition to FindNeighbors and FindClusters. Differential gene expression between clusters was performed using the FindMarkers function with the Wilocox test in Seurat. Violin plots and individual UMAP plots were all generated using the Seurat toolkit VlnPlot and FeaturePlot functions, respectively. Heatmaps were generated utilizing the pheatmap package (version 1.0.12).

Single Nucleus RNA Sequencing

Raw sequencing reads were demultiplexed to FASTQ format files using bcl2fastq (Illumina; version 2.20.0). Digital expression matrices were generated from the FASTQ files using Cell Ranger (Zheng et al., 2017)(version 6.1.2) with the option to include intronic reads (--include-introns). Reads were aligned against the GRCm38 mouse genome assembly and gene counts were obtained, per-droplet, by summarizing exonic and intronic UMIs that overlapped with the GENCODE mouse annotation (release 24) for each gene symbol. In order to adjust for downstream effects of ambient RNA expression within mouse nuclei, we used the "remove-background" module from CellBender (Fleming et al., 2022) (version 0.2.0) to remove counts due to ambient RNA molecules from the count matrices and to estimate the true cells. Genes were subsequently filtered such that only genes detected in two or more cells and with at least 6 total counts (across all cells) were retained. Sample demultiplexing via hashtag oligonucleotide sequences (HTOs) was performed with the Cumulus sc/snRNA-Seq processing pipeline (Li et al., 2020). Specifically, HTO quantification was performed with the Cumulus Tool on Feature Barcoding, which provided a cell-by-HTO count matrix. This HTO count matrix, along with the gene count matrices generated via Cell Ranger (above) were used to assign each cell to their respective sample(s) with the demuxEM program. Only cells that were identified as singlets were retained (i.e. no cells identified as a multiplet or unassignable) in the per-sample CellBender-ed gene count matrices.

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Cellbender output files were read into R (version 4.1.1) and processed utilizing the standard Seurat CCA and later RPCA integration workflows (version 4.3.0). Each of the hashed samples (24 in total) were merged with their respective pair to have a total of twelve samples consisting of six different groups. Each sample was filtered prior to downstream analysis based on their nCount_RNA, nFeature_RNA, and mitochondrial percentages. Samples were then normalized using a LogNormalization method with a scaling factor of 10000 followed by FindVariableFeatures using a Variance-Stabilizing Transformation as the method with the top 2000 features to be returned. The FindIntegrationAnchors function using the CCA reduction method and IntegrateData was utilized to integrate the data together. The integrated data-set was then scaled on which mitochondrial percentage was regressed. A principal component analysis was performed in which only the top 18 dimensions were retained. Uniform Manifold and Projection (UMAP), FindNeighbors, and FindClusters with a resolution of 0.4 was performed on the dataset. To remove doublets in the dataset, we used the package scDblFinder (1.8.0) and their function scDblFinder with the parameters of samples set to our twelve samples, dbr set to NULL, dbr.sd set to 1, clusters set to FALSE, and multiSampleMode set to split. The object was then subsetted to only contain expected singlets. Differential gene expression between clusters was performed using the FindMarkers function with the Wilocox test in Seurat. Violin plots and individual UMAP plots were all generated using the Seurat toolkit VlnPlot and FeaturePlot functions, respectively. Heatmaps were generated utilizing the dittoSeq package (1.9.1) and pheatmap package (version 1.0.12).

After identifying the adipocyte population, we subsetted our object on that population, extracting the raw RNA counts on the cells for each of the six samples (YTN, OTN, Y3D, O3D, Y14D, O14D) (Y is young, O is “Old” or as referred to in this paper, Aged). These samples were then integrated together using the standard RPCA integration workflow. There was no further filtering done on the reintegrated adipocyte population. Samples were normalized using a LogNormalization method with a scaling factor of 10000 followed by FindvariableFeatures using a Variance-Stabilizing Transformation as the method with the top 2000 features to be returned. The function SelectIntegrationFeatures was performed on the dataset where it was then scaled on which mitochondrial percentage was regressed, and principal components were found using the ScaleData and RunPCA functions. The FindIntegrationAnchors function using the ROCA reduction method and a k.anchors of 20 and IntegrateData was utilized to integrate the data together. After integration, the dataset was then scaled in which mitochondrial percentage was regressed on again. A principal component analysis was performed in which only the top 18 dimensions were retained. Uniform Manifold and Projection (UMAP), FindNeighbors, and

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FindClusters with a resolution of 0.2 was performed on the dataset. Differential gene expression between clusters was performed using the FindMarkers function with a Wilcoxon signed-rank test as the method in Seurat. Violin plots and individual UMAP plots were all generated using the Seurat toolkit VlnPlot and FeaturePlot functions, respectively. Heatmaps were generated utilizing the dittoSeq package (1.9.1) and pheatmap package (version 1.0.12).

Enrichment analysis was performed on the positively expressed genes with a $\log_2$ fold change (LFC) > 0.25 and a $P_{adjusted}$ value < 0.01 on comparison of the young 14 days cold and old 14 days cold groups in the DNL high cluster. The generated gene list, which was in order of significance, was fed into g:Profiler (version 0.2.1) using default parameters except with modifications to query as an ordered query against the 'mmusculus' database, a gSCS correction method for multiple testing, with domain scope set to annotated, and sources set to the Reactome database. The top six enriched pathways yielded from the database were taken and displayed in order of $P_{adjusted}$ value.

Statistical methods

All bar graphs represent the mean ± SE. A Student's t-test was used when 2 groups were compared. Where multiple conditions were compared, we applied a Holm-Šidák correction for multiple comparisons. p values are indicated by asterisks and defined as *p < 0.05, **p < 0.01 and ***p < 0.001. All statistics were calculated with GraphPad Prism Version 9.5.0.

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