

Naturally occurring p16^{Ink4a}-positive cells shorten healthy lifespan

Darren J. Baker¹, Bennett G. Childs², Matej Durik¹, Melinde E. Wijers¹, Cynthia J. Sieben², Jian Zhong⁴, Rachel A. Saltness¹, Karthik B. Jeganathan¹, Grace Casaclang Verzosa³, Abdulmohammad Pezeshki⁴, Khashayarsha Khazaie⁴, Jordan D. Miller³ & Jan M. van Deursen^{1,2}

Cellular senescence, a stress-induced irreversible growth arrest often characterized by expression of p16^{Ink4a} (encoded by the *Ink4a*/*Arf* locus, also known as *Cdkn2a*) and a distinctive secretory phenotype, prevents the proliferation of preneoplastic cells and has beneficial roles in tissue remodelling during embryogenesis and wound healing. Senescent cells accumulate in various tissues and organs over time, and have been speculated to have a role in ageing. To explore the physiological relevance and consequences of naturally occurring senescent cells, here we use a previously established transgene, *INK-ATTAC*, to induce apoptosis in p16^{Ink4a}-expressing cells of wild-type mice by injection of AP20187 twice a week starting at one year of age. We show that compared to vehicle alone, AP20187 treatment extended median lifespan in both male and female mice of two distinct genetic backgrounds. The clearance of p16^{Ink4a}-positive cells delayed tumorigenesis and attenuated age-related deterioration of several organs without apparent side effects, including kidney, heart and fat, where clearance preserved the functionality of glomeruli, cardio-protective K_{ATP} channels and adipocytes, respectively. Thus, p16^{Ink4a}-positive cells that accumulate during adulthood negatively influence lifespan and promote age-dependent changes in several organs, and their therapeutic removal may be an attractive approach to extend healthy lifespan.

Cellular senescence is a well-established cancer defence mechanism that has also been proposed to have roles in ageing and age-associated diseases, presumably through the depletion of stem and progenitor cells, and the adverse actions of the senescence-associated secretory phenotype, which consists of many proinflammatory cytokines and chemokines, matrix metalloproteinases and growth factors^{1–3}. Consistent with this idea is the observation that interference with senescent cell accumulation in BubR1 progeroid mice delays several of the ageing-associated disorders that these animals develop^{4,5}. However, because progeroid syndromes do not mimic the complex degenerative changes of ageing completely, the relevance of these findings has remained unclear. Furthermore, recent studies showing that senescent cells have beneficial effects in injury repair and tissue remodelling^{6–10} have called into question the simplistic view of senescence as only a driver of age-dependent pathologies, raising the specter that senescent cell clearance might remove useful cells in addition to detrimental ones. Here we investigated the identity and physiological effect of naturally occurring senescent cells using *INK-ATTAC* (hereafter termed *ATTAC*)⁴, a transgenic mouse model that expresses the FK506-binding protein–caspase 8 (FKBP–Casp8) fusion protein and green fluorescent protein (GFP) under the control of a minimal *Ink4a* (also known as *Ink4a*/*Arf* or *Cdkn2a*) promoter fragment transcriptionally active in senescent cells^{4,11}. Earlier we have shown that, in BubR1 progeroid mice, *ATTAC* ablates p16^{Ink4a}-positive senescent cells upon administration of AP20187 (AP), a dimerizer that activates FKBP-fused Casp8 (ref. 4). Our first objective was to validate the properties of *ATTAC* in naturally occurring p16^{Ink4a}-positive senescent cells.

ATTAC clears senescent adipocyte progenitor cells

Our initial validation was focused on fat. We collected GFP⁺ and GFP⁻ cell populations from inguinal white adipose tissue (iWAT) of

12-month-old *ATTAC* mice by FACS (Fig. 1a). GFP⁺ cells expressed much higher levels of *Ink4a* and *FKBP-Casp8* than GFP⁻ cells, as well as a broad panel of senescence markers (Fig. 1b). GFP⁺ cells, but not GFP⁻ cells, were also highly positive for senescence-associated-β-galactosidase (SA-β-Gal; Fig. 1c). Furthermore, intact iWAT from aged, but not young *ATTAC* mice had SA-β-Gal activity, but less than iWAT of BubR1 progeroid mice, a difference also reflected in *Ink4a*, *FKBP-Casp8* and GFP transcript levels (Extended Data Fig. 1a, b).

iWAT of 18-month-old *ATTAC* mice treated bi-weekly with AP from 12 months onwards had eightfold less GFP⁺ adipocyte progenitors than vehicle-injected controls, although total progenitor cell numbers remained unchanged (Fig. 1d and Extended Data Fig. 1c). SA-β-Gal staining and quantitative reverse transcriptase PCR (qRT-PCR) analysis of senescence markers confirmed that *Ink4a*-positive senescent cells in iWAT increased between 12 and 18 months, and that AP eliminated most of these cells (Fig. 1e and Extended Data Fig. 1d). Consistent with senescence of progenitor cells, transmission electron microscopy (TEM) on SA-β-Gal-stained iWAT showed that X-Gal crystals were present in small perivascular cells rather than endothelium, white blood cells or adipocytes (Fig. 1f). X-Gal crystals were found in 0.2% and 1.6% of total iWAT cells from AP-treated and control mice, respectively (Fig. 1g).

Clearance of *Ink4a*-positive cells prevented loss of fat mass occurring between 12 and 18 months (Fig. 1h, i and Extended Data Fig. 1e). Age-dependent fat tissue dysfunction is characterized by decreased adipogenesis and adipocyte atrophy¹². Consistent with this, adipocyte size decreased between 12 and 18 months of age (Fig. 1j), as did transcript levels of two key transcriptional regulators of adipogenesis, *Pparg* and *Cebpa* (Fig. 1k). AP treatment of *ATTAC* mice prevented these decreases. Collectively, these data indicate that senescence contributes to age-dependent fat tissue alterations.

¹Department of Pediatric and Adolescent Medicine, Mayo Clinic College of Medicine, Rochester, Minnesota 55905, USA. ²Department of Biochemistry and Molecular Biology, Mayo Clinic College of Medicine, Rochester, Minnesota 55905, USA. ³Division of Cardiovascular Surgery, Mayo Clinic College of Medicine, Rochester, Minnesota 55905, USA. ⁴Department of Immunology, Mayo Clinic College of Medicine, Rochester, Minnesota 55905, USA.

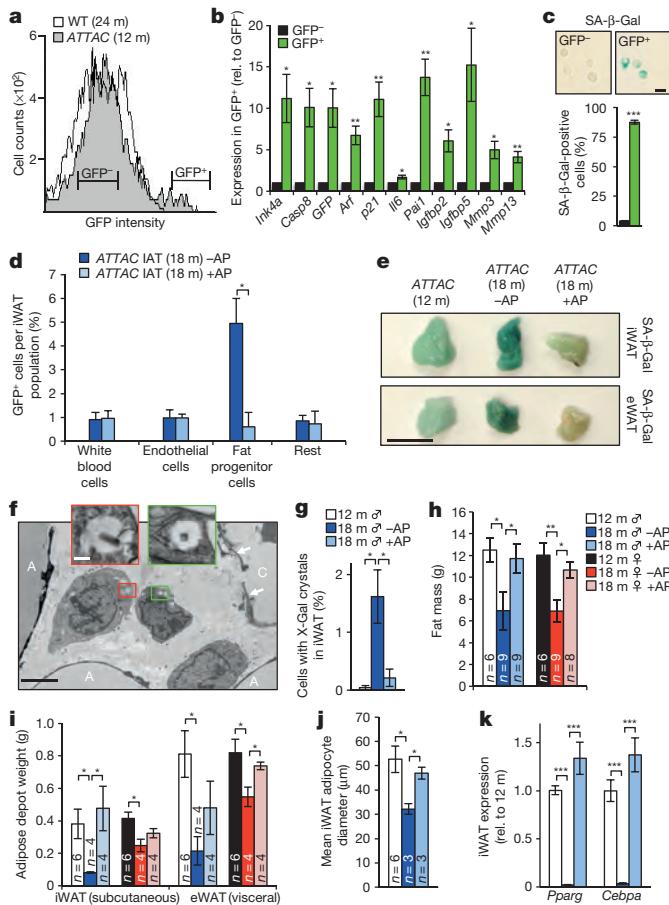


Figure 1 | Clearance of senescent fat progenitor cells attenuates age-related lipodystrophy. **a**, FACS profiles of single-cell suspensions from iWAT of the indicated 12- and 24-month-old (m) mice. **b**, GFP⁺ and GFP⁻ cell populations from iWAT of 12-month-old ATTAC mice (see **a** for sorting brackets) analysed by qRT-PCR ($n = 6$ mice). *p21* is also known as *Cdkn1a*; *Pail* is also known as *Serpine1*. **c**, SA-β-Gal activity in GFP⁺ and GFP⁻ iWAT cells ($n = 3$ mice). **d**, GFP⁺ cells in the indicated iWAT (IAT) cell populations ('rest' represents the iWAT vascular stromal fraction minus leukocytes, endothelial cells and progenitors). **e–i**, Fat-related analyses of C57BL/6 ATTAC mice before treatment (12 months) or after 6 months of treatment with vehicle (18 months –AP) or AP (18 months +AP). **e**, SA-β-Gal activity in iWAT and epididymal WAT (eWAT). **f**, Electron micrograph showing perivascular X-Gal-positive cells from an 18-month-old vehicle-treated C57BL/6 ATTAC male. A, adipocyte; C, capillary. Arrows mark endothelial cells. **g**, Quantification of iWAT cells containing X-Gal crystals ($n = 4$ mice per treatment). **h**, Fat mass measurements. **i**, iWAT and eWAT depot weights. **j**, Mean adipocyte diameters in iWAT. **k**, Expression of adipogenesis markers in iWAT ($n = 4$ mice per group). Scale bars, 10 μm (**c**), 0.5 cm (**e**), 2 μm (**f**) and 200 nm (**f**, inset). Error bars indicate s.e.m. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ (one-sample *t*-tests using a theoretical mean of 1 (**b**), and unpaired two-tailed *t*-tests (**c**, **d**, **g–k**).

Adipose tissue of young ATTAC mice lacked SA-β-Gal activity but contained p16^{Ink4a} (Extended Data Fig. 1a, f–h). This p16^{Ink4a} pool did not decline after AP treatment. Similar results were obtained with early passage ATTAC MEFs (Extended Data Fig. 1i–k), indicating that baseline *Ink4a* promoter activity in non-senescent cells is insufficient for FKBP-Casp8-mediated apoptosis. Furthermore, ATTAC lacks *Ink4a* promoter elements required for transgene induction in replicating pre-neoplastic cells that robustly express endogenous *Ink4a* owing to Rb inactivation and AP fails to kill these cells (Extended Data Fig. 2a–g). ATTAC was also not induced in peripheral blood T lymphocytes that robustly engage endogenous *Ink4a* with ageing without concomitant expression of several senescence markers^{2,13} (Extended Data Fig. 2h),

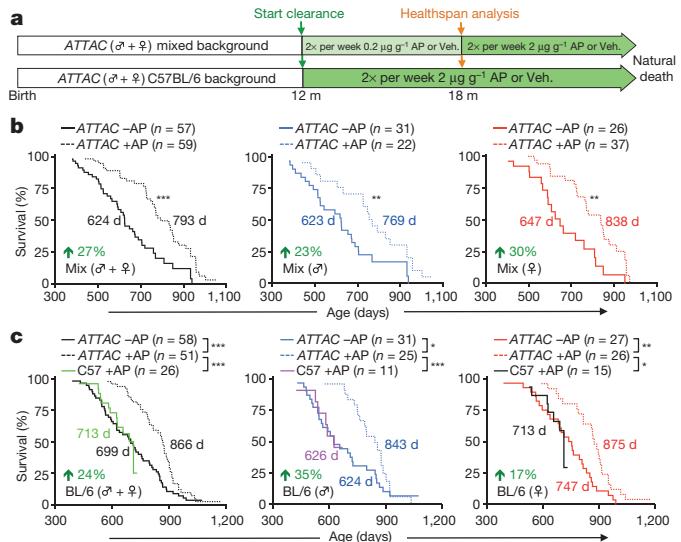


Figure 2 | Senescent cell clearance extends lifespan. **a**, Study design for clearance of senescent cells in mixed and C57BL/6 mouse cohorts. Healthspan analysis was done at 18 months, an age at which relatively few mice in vehicle (Veh.)- or AP-treated groups have died, and bias owing to selection for long-lived animals is unlikely. **b**, **c**, Survival curves for vehicle-treated (–AP) and AP-treated (+AP) mixed (**b**) and C57BL/6 (**c**) mice. Median survival (in days, **d**) and percentage increase in median survival are indicated. We note that median lifespans of our vehicle-treated cohorts are similar to those of wild-type mice administered AP (**c**). * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ (log-rank tests).

further indicating that transgene induction is selective for senescence. However, these limited analyses certainly do not exclude the possibility that other *Ink4a*-positive non-senescent cells engage ATTAC and die after AP exposure (Supplementary Information).

Clearance by ATTAC is partial and tissue selective

To extend our analysis of the properties of ATTAC, we analysed the transcript levels of *Ink4a*, *FKBP-Casp8*, GFP and a panel of senescence markers in a broad spectrum of tissues of 2-, 12- and 18-month-old untreated ATTAC mice, including skeletal muscle, eye, kidney, lung, heart, liver, colon and spleen. ATTAC mice treated with AP between 12 and 18 months were included to assess senescent cell clearance rates. *Ink4a* expression markedly increased between 12 and 18 months in all tissues examined, which coincided with the induction of *FKBP-Casp8*, GFP and several senescence markers (Extended Data Fig. 3a). Increased expression of these transcripts was blunted to varying degrees by AP treatment in all tissues examined except colon and liver, indicating that the ATTAC system eliminates *Ink4a*-positive senescent cells in a partial and tissue/organ selective fashion. Blunting of age-dependent increases in *Il6*, *Il1a* and *Tnfα* expression in fat, skeletal muscle and kidney by AP treatment (Extended Data Fig. 3b) suggests that *Ink4a*-positive cell clearance ameliorates inflammation in these tissues.

p16^{Ink4a}⁺ cells shorten lifespan and healthspan

To examine the effect of p16^{Ink4a}-positive cell clearance on health and lifespan, we sequentially established two cohorts of ATTAC transgenic mice (Fig. 2a). The initial cohort was on a C57BL/6-129Sv-FVB mixed genetic background fed a diet containing 9% fat. We note that this diet shortens lifespan compared to diets with 5% fat typically used in lifespan studies (Extended Data Fig. 4a, b and Supplementary Information). The later cohort was on a congenic C57BL/6 background fed a standard 5% fat diet. At 12 months of age, when p16^{Ink4a}⁺ cells started to accumulate in several tissues (Extended Data Figs 1d and 3a), mice were injected twice a week with AP or vehicle until they became moribund or died of natural causes. Mice separate from the longevity cohorts were examined for a series of age-sensitive outcomes at

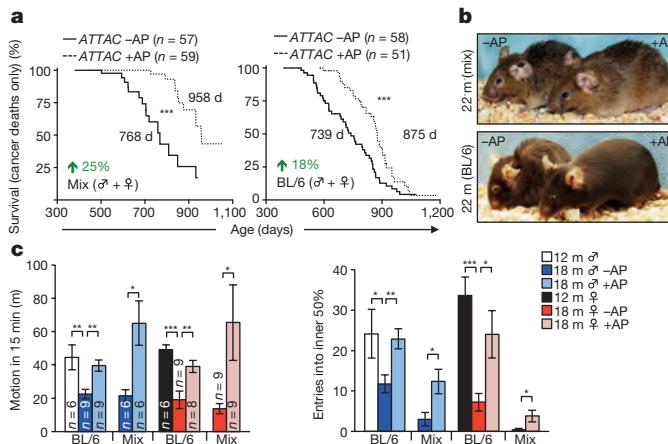


Figure 3 | Clearance of senescent cells prolongs healthspan. **a**, Survival curves of ATTAC mice dying of cancer (mice that had an overt tumour at time of death; mice with lymphomas, sarcomas and carcinomas were included, mice without tumours were censored). Median survival and percentage increase are indicated. **b**, Representative images of aged mice with and without senescent cell clearance. **c**, Spontaneous movement and exploratory behaviour of ATTAC mice analysed by the open field test. Error bars indicate s.e.m. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ (log-rank test (**a**) and unpaired two-tailed *t*-test (**c**)).

18 months, an age at which relatively few mice in each of the cohorts had died. Data for both sexes combined showed that median lifespans of mixed and C57BL/6 AP-treated animals were increased by 27% and 24%, respectively. Median lifespans for each sex separately were also significantly extended in AP-treated cohorts irrespective of genetic background, with increases ranging from 17% to 35% (Fig. 2b, c).

Maximum lifespan¹⁴ was significantly increased for mixed AP-treated males and females combined ($P = 0.0295$), but not for females and males individually. Maximum lifespan was not extended for C57BL/6 AP-treated animals, either combined or separately. Importantly, AP treatment of mice lacking the ATTAC transgene did not improve lifespan (Fig. 2c). We note that the median lifespan of vehicle-treated C57BL/6 males, but not females, was short of the normal range of lifespans for unmanipulated males of this strain at different laboratories^{15–28} (Extended Data Fig. 4c, d), suggesting that repetitive vehicle injection stress may have negatively affected C57BL/6 male longevity (Supplementary Information).

In both cohorts, AP treatment had no effect on the incidence or spectrum of macroscopically detectable tumours at autopsy, although tumour latency was increased (Fig. 3a and Extended Data Fig. 5a–d). Median lifespan extensions of AP-treated mice dying without tumours ranged from 24% to 42% (Extended Data Fig. 5e), indicating that increased longevity was not merely due to a tumour-protective effect. AP-treated mice were overtly indistinguishable from vehicle-injected littermates at 18 months of age, but typically had a healthier appearance by 22 months (Fig. 3b). AP treatment delayed cataract formation in both males and females on a C57BL/6 background (Extended Data Fig. 5f, g). Despite a lack of overt difference at 18 months, AP-treatment prevented age-dependent reductions in both spontaneous activity and exploratory behaviour measured by open-field testing (Fig. 3c), which was independent of sex and genetic background.

Extended tests on these mice showed no differences in motor coordination and balance, memory, exercise ability or muscle strength (Extended Data Fig. 6), indicating that 6 months of p16^{Ink4a}-positive cell clearance did not affect these age-sensitive traits. Similarly, age-related changes in the circulating haematopoietic profile, including regulatory T-cell levels, were also not affected (Extended Data Fig. 7). At 18 months, fasting glucose levels, glucose tolerance, insulin sensitivity and circulating Igf1 levels were not significantly different in AP- and vehicle-treated C57BL/6 ATTAC females, as was signalling downstream

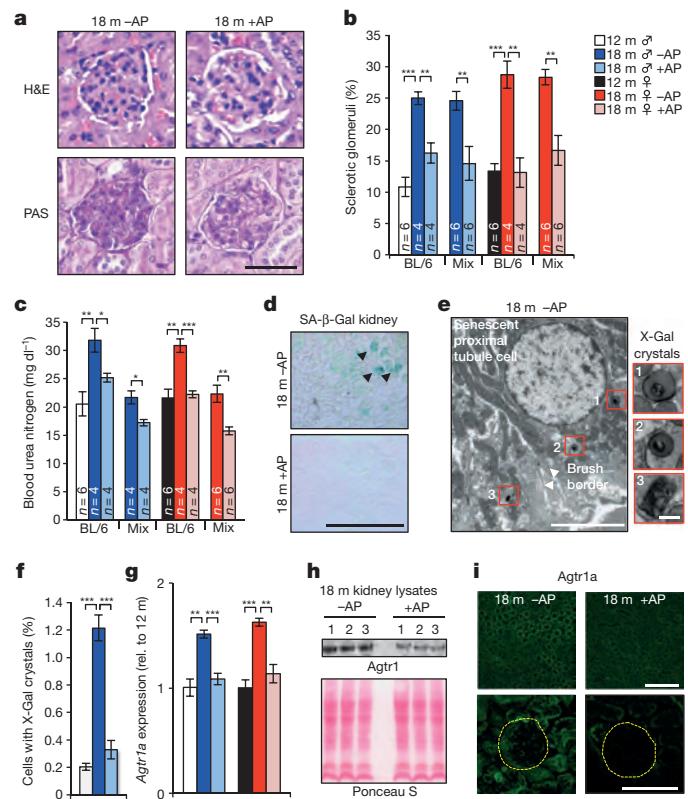


Figure 4 | Senescent cells cause glomerulosclerosis, kidney dysfunction and renal RAAS hyperactivity. **a**, Images of sclerotic (left) and normal (right) glomeruli from the indicated mice. H&E, haematoxylin and eosin; PAS, periodic acid-Schiff. **b**, Quantification of sclerotic glomeruli. **c**, Measurements of blood urea nitrogen levels. **d**, SA-β-Gal-stained kidney sections. **e**, Electron micrograph showing a X-Gal crystal-containing renal epithelial cell with brush border membrane (arrowheads). Insets show X-Gal crystal close-ups. **f**, Percentage of cells with X-Gal crystals in renal sections ($n = 5$ TEM grids for each treatment group). **g**, Renal expression of *Agtr1a* analysed by qRT-PCR ($n = 4$ mice per group). **h**, Western blot of kidney lysates probed for *Agtr1a* ($n = 3$ mice per treatment group). Ponceau S staining served as loading control. **i**, Immunostaining of kidney sections for *Agtr1a*. Yellow circles denotes glomeruli. Scale bars, 50 μm (**a** and **i**, bottom), 250 μm (**d**), 5 μm (**e**, insets) and 100 μm (**i**, top). Error bars indicate s.e.m. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ (unpaired two-tailed *t*-tests). For gel source data, see Supplementary Fig. 1. All mice in **d–i** were C57BL/6 ATTAC.

of Igf1 and insulin receptors in fat, kidney and muscle, three tissues where we observed clearance of p16^{Ink4a}⁺ cells (Extended Data Fig. 8).

Renal epithelial cell senescence and glomerulosclerosis

To further investigate the effect of p16^{Ink4a}⁺ cells on physiological functions that change with age²⁹, we focused on kidney and heart, two vital organs in which we observed ATTAC-mediated clearance. Aged kidneys are characterized by the formation of sclerotic glomeruli, which affect glomerular filtration rates, impair kidney function, and lead to increased blood urea nitrogen levels^{30,31}. Indeed, glomerulosclerosis significantly increased between 12 and 18 months in vehicle-treated ATTAC mice. AP treatment markedly reduced glomerulosclerosis independent of sex and genetic background (Fig. 4a, b), which correlated with attenuated age-related increases in blood urea nitrogen (Fig. 4c), indicating preserved kidney function. SA-β-Gal staining of kidney sections confirmed that AP-mediated disposal of senescent cells was quite efficient (Fig. 4d). By TEM, we observed X-Gal crystals in 0.3% and 1.2% of renal cells of 18-month-old treated and untreated mice, respectively (Fig. 4e, f). Surprisingly, SA-β-Gal⁺ cells were not located in the glomeruli but in proximal tubules (Fig. 4e), raising the

question as to how senescent tubular brush-border epithelial cells might promote glomerulosclerosis.

Angiotensin receptor blockers attenuate age-related glomerulosclerosis under normotensive conditions, which has led to the idea that overactivation of the local renin-angiotensin-aldosterone system (RAAS) drives the formation of sclerotic glomeruli^{31,32}. Consistent with this, kidney transcript levels of a key component of this system, angiotensin receptor 1a (*Agtr1a*), increased between 12 and 18 months (Fig. 4g). By contrast, no such increase was observed in AP-treated mice. Western blotting confirmed that *Agtr1a* protein levels were lower in AP-treated kidney samples (Fig. 4h). Both renal tubules and glomeruli contributed to this decline, as demonstrated by immunolabelling of kidney sections for *Agtr1a* (Fig. 4i). These data suggest that senescent renal epithelial cells may produce senescence-associated secretory phenotype components that hyperactivate the local RAAS in kidney.

p16^{Ink4a}⁺ cells contribute to cardiac ageing

Hearts of 12-month-old mice showed SA- β -Gal activity at the atrial and ventricular surface (Fig. 5a), which increased with ageing in vehicle-treated but not AP-treated mice. TEM revealed that ciliated epithelial cells and fibroblasts in the pericardium contained X-Gal crystals

(Fig. 5b, c). We also observed SA- β -Gal⁺ smooth muscle cells in the aortic root wall of vehicle-treated animals (Fig. 5a and Extended Data Fig. 9a). At 18 months, vehicle- and AP-treated *ATTAC* mice analysed by echocardiography showed no significant differences in heart rate, left ventricular mass, thickness and diameter, ejection fraction and fractional shortening, all of which were also unchanged from 12-month-old mice (Extended Data Fig. 9b–g). Cardiac ageing at the histological level is characterized by a loss of ventricular cardiomyocytes due to decreasing ability to replace apoptotic or necrotic cardiomyocytes, inducing hypertrophy of the remaining cardiomyocytes³³. Morphometric analysis of heart sections showed that ventricular wall thickness was the same in vehicle- and AP-treated animals, regardless of sex (Fig. 5d). Ventricular cardiomyocytes of AP-treated mice, however, were much smaller (Fig. 5e, f), suggesting that they had more cardiomyocytes than vehicle-treated mice. Taken together, these data suggest that p16^{Ink4a}-positive cells are key drivers of this age-related cardiac phenotype.

Cardiac ageing is also characterized by decreasing stress tolerance, which has been attributed to decreasing numbers of ATP-sensitive potassium (K_{ATP}) channels in the sarcolemma of cardiac myocytes due to age-related reductions in the expression of *Sur2a*, a key

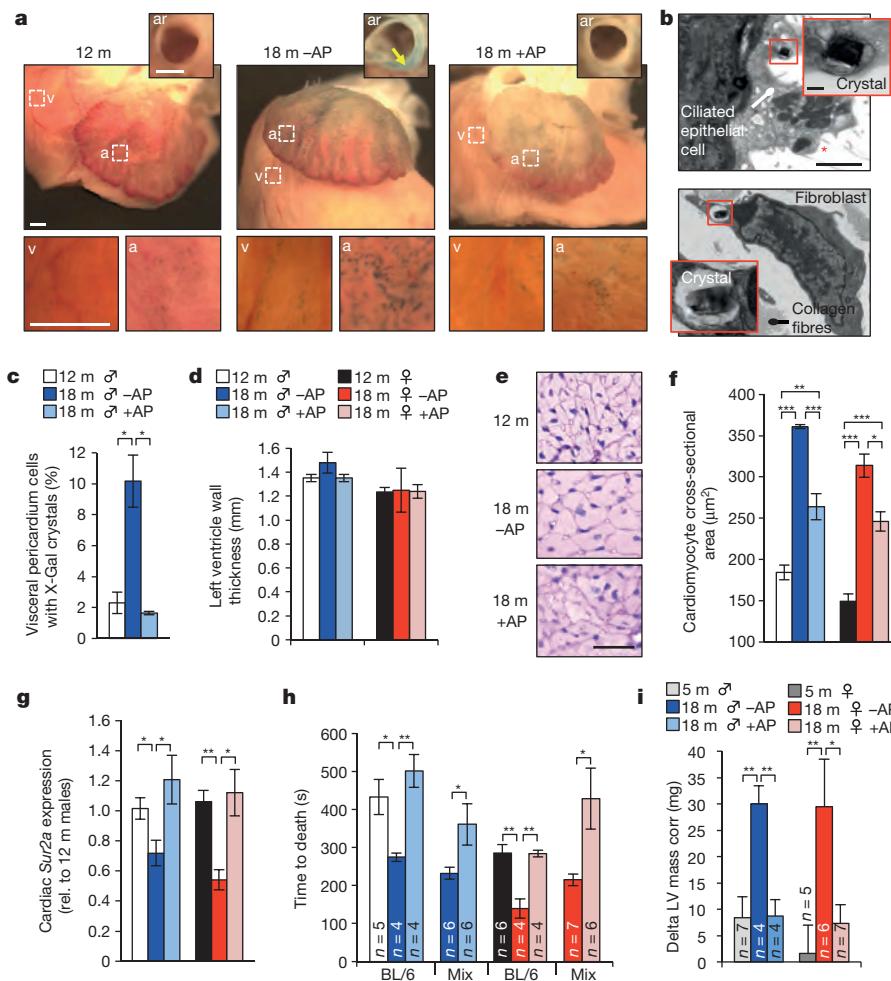


Figure 5 | Senescent cells promote age-related cardiomyocyte hypertrophy and loss of cardiac stress tolerance. **a**, SA- β -Gal-stained hearts. Insets show aortic roots (ar) from a transverse plane (arrow marks the aortic root wall) or close-ups of the ventricular (v) and arterial (a) boxed areas. **b**, Electron micrographs of X-Gal-positive cells in the pericardium (red asterisk marks cilia). Insets show close-ups of X-Gal crystals. **c**, Quantification of cells with X-Gal crystals in the visceral pericardium ($n = 4$ mice per treatment). **d**, Measurements of left ventricle wall thickness ($n = 4$ mice per group). **e**, Representative cardiomyocyte

cross-sectional images ($n = 4$ mice per group). **f**, Quantification of **e**. **g**, Analysis of *Sur2a* expression in hearts by qRT-PCR ($n = 4$ mice per group). **h**, Cardiac stress resistance determined by measuring the time to death after injection of a lethal dose of isoproterenol. **i**, Change in left ventricular (LV) mass in response to sublethal doses of isoproterenol (10 mg kg^{-1}) after ten doses administered over 5 days. Scale bars, 1 mm (**a**), 2 μm (**b**) and 200 nm (**b**, inset). Error bars indicate s.e.m. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ (unpaired two-tailed *t*-tests). All mice, except for **h**, were C57BL/6 *ATTAC*.

regulatory subunit of K_{ATP} channels³⁴. Cardiac *Sur2a* (also known as *Abcc9*) expression indeed decreased between 12 and 18 months in vehicle-treated mice (Fig. 5g), but no such decline was observed in AP-treated mice, suggesting that cardiac stress tolerance was preserved. To test this, we measured the time to death from arrhythmogenesis after injection of 580 mg kg⁻¹ of the β-adrenergic agonist isoproterenol³⁵. Consistent with age-related loss of cardiac stress resistance, 18-month-old vehicle-treated mice died faster than 12-month-old mice (Fig. 5h). By contrast, the time to death was not accelerated in AP-treated mice. In a second, more physiological stress test, we conducted echocardiographic measurements of ventricular mass before and after eliciting cardiac stress over a 6-day period, by administering 10 mg kg⁻¹ isoproterenol twice a day. Cardiac mass significantly increased in 18-month-old vehicle-treated mice, whereas AP-treated mice were capable of handling the applied stress without such adaptive response, similar to young mice (Fig. 5i).

We also examined whether AP-treatment caused any off-target or detrimental effects. Wild-type mice lacking *ATTAC* did not show healthspan improvements when treated with AP (Extended Data Fig. 9h–l). Consistent with a beneficial role of senescent cells only for the duration of wound repair^{6–8}, 18-month-old AP-treated *ATTAC* mice repaired cutaneous wounds when drug administration was suspended during healing (Extended Data Fig. 10a–c). When AP was administered during wound closure, healing was delayed with similar kinetics as 4- or 18-month-old *ATTAC* mice without previous AP treatment, indicating that acute senescence mechanisms are preserved with ageing and not influenced by constitutive clearance of senescent cells³. Furthermore, 18-month-old AP-treated mice showed no evidence of increased fibrosis in skin and other tissues, despite a role for senescent cells in limiting fibrosis during tissue repair (Extended Data Fig. 10d).

Discussion

Here we eliminated p16^{Ink4a}⁺ cells from non-progeroid mice using *ATTAC* to begin to address how senescent cells influence health and lifespan. We observe median lifespan extensions in AP-treated *ATTAC* mice on two distinct genetic backgrounds and diets, indicating that age-related accumulation of p16^{Ink4a}⁺ cells negatively affects longevity. It will be useful to optimize senescent cell removal protocols and methods further because the longevity of male C57BL/6 mice seemed negatively affected by repetitive vehicle injection stress, and because clearance was partial and several key tissues were refractory to clearance, including liver and colon. This would be particularly relevant for further studies of maximum lifespan, extension of which is thought to be reflective of a more generalizable ‘anti-ageing’ effect²⁹ (Supplementary Information).

These methodological caveats aside, we find that removal of p16^{Ink4a}⁺ cells from midlife on delays the progression of neoplastic disease irrespective of genetic background and diet. Clearance had no effect on the spectrum or incidence of post-mortem tumours, which is consistent with the hypothesis that senescent cells help create a tissue microenvironment that promotes tumour progression¹. In addition, several age-dependent changes²⁹, including alterations in fat, eye, heart and kidney, as well as the age-dependent decline in spontaneous activity and exploratory behaviour, occur more slowly during a six-month period of p16^{Ink4a}⁺ cell clearance starting at midlife. Complementary mechanistic studies suggest that local p16^{Ink4a}⁺ cells in fat, kidney and heart exert their effects through distinct mechanisms, involving progenitor cell dysfunction, RAAS overactivation, and *Sur2a* downregulation, respectively, although systemic effects cannot be excluded given the global nature of the clearance method applied here.

Thus, our data best fit a model in which p16^{Ink4a}⁺ cells act to shorten healthy lifespan by promoting tumour progression and age-dependent changes that functionally impair certain tissues and organs, including vital organs such as kidney and heart. This, together with the key observation that elimination of p16^{Ink4a}⁺ cells is not associated with any overt detrimental effects raises the possibility that this approach may

be useful to treat aspects of age-related functional decline, age-related diseases that involve senescent cells, or side effects of therapies that create senescent cells³⁶.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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Supplementary Information is available in the online version of the paper.

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Author Contributions D.J.B. performed all lifespan and most healthspan analyses on ATTAC mice. B.G.C. designed and conducted experiments to identify and quantify X-gal-positive cells by TEM, and analysed mice for cardiomyocyte hypertrophy and local RAAS activity in kidney. M.E.W., J.Z. and R.A.S. assisted with various aspects of healthspan analyses: the extent of their contributions is reflected in the authorship order. C.J.S. conducted the lifespan analysis of C57BL/6-129Sv/E hybrid mice on diets containing 5% or 9% fat. K.B.J. investigated somatotrophic axis signaling. G.C.C.V., J.D.M. and M.D. analysed resting heart functions by echocardiography. M.D. designed and conducted cardiac stress tests. A.P. and K.K. analysed leukocyte subpopulations. J.M.v.D., D.J.B. and B.G.C. wrote the paper with input from all co-authors. J.M.v.D. directed and supervised all aspects of the study in collaboration with D.J.B.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare competing financial interests: details are available in the online version of the paper. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to J.M.v.D. (vandeursen.jan@mayo.edu) or D.J.B. (baker.darren@mayo.edu).

METHODS

Mouse strains and drug treatments. All studies described using ATTAC mice were performed on transgenic line 3, which contains 13 copies of the transgene inserted into a single locus (data available on request). The generation and characterization of the ATTAC transgenic line has been previously described in detail⁴. Two cohorts of ATTAC mice were consecutively established and analysed. The first cohort consisted of mice on a mixed 129Sv (40% ± 5%) × 57BL/6J (35% ± 5%) × FVB (20% ± 5%) genetic background as determined by Harlan Laboratories using established single nucleotide polymorphism (SNP) panels (Supplementary Table 1). These mice were fed an irradiated pelleted breeder chow diet *ad libitum* for the entire duration of the study: LabDiet product 5058, with 9% fat content (21.635% calories from fat). Mice from this cohort were randomly assigned to be injected with AP20187 (AP; B/B homodimerizer, Clontech) or vehicle twice a week beginning at 12 months of age. Dosing was 0.2 µg AP20187 per g body weight between 12 and 18 months (the same dose as previously used for senescent cell clearance in BubR1 progeroid mice; see ref. 4), and 2.0 µg AP per g body weight from thereon. The second cohort was established ~1.5 years later after completion of ATTAC line 3 backcrossing onto a pure C57BL/6J genetic background (Jackson Lab stock number 000664). Detailed breeding information for the C57BL/6 ATTAC cohort is provided in Supplementary Table 2. For the entire duration of the study, congenic ATTAC transgenic mice were maintained *ad libitum* on standard irradiated pelleted chow diet: LabDiet product 5053 with 5% fat content (13.205% calories from fat). The number of mice in the C57BL/6J cohort was increased compared to the mixed cohort to allow for more comprehensive healthspan analyses at 18 months of age. The C57BL/6J cohort was randomly assigned to receive either 2.0 µg AP per g body weight or vehicle from 12 months until the end of life. Non-transgenic mice from C57BL/6J ATTAC transgenic crosses were used to establish the control cohort for confirmation that AP had no effect on healthspan in the absence of the ATTAC transgene. *BubR1*^{H/H};ATTAC mice used in this study were generated as previously described⁴. Animals were housed in a pathogen-free barrier environment throughout the duration of the study and kept on a 12-h light–dark cycle. Specifically, mice were housed 5 per cage in static autoclaved HEPA-ventilated microisolator cages measuring 446 cm² (27 × 16.5 × 15.5 cm), which are opened only within class II biosafety cabinets. Restricted entry to the room requires key card access to unlock the door. Entrance into the barrier facility requires wearing autoclaved gowns, disposable gloves, caps and shoe covers. Personnel are not allowed to enter any other rodent facility before entry into the barrier. Mouse colonies in this facility are monitored through contact sentinels (one cage per rodent rack), which are evaluated quarterly for (and are free of) the following agents: Sendai virus, pneumonia virus of mice (PVM), mouse hepatitis virus (MHV), minute virus of mice (MVM), Theiler's murine encephalomyelitis virus (TMEV strain GDVII), reovirus, rotavirus (EDIM), mouse parvovirus (MPV strain 1 and 2), murine norovirus (MNV), *Mycoplasma pulmonis*, *Aspiculuris tetraptera* and *Syphacia* spp. In addition, the following are annually screened for (and free of) these agents: lymphocytic choriomeningitis virus (LCMV), ectromelia virus (mousepox), K virus, polyoma virus, mouse adenovirus (MAV type 1 and 2), hantavirus, Prospect Hill virus (PHV), mouse cytomegalovirus (MCMV), lactate dehydrogenase elevating virus (LDEV) *Encephalitozoon cuniculi*, cilia-associated respiratory bacillus (CARB), mouse thymic virus (MTV, MTLV), *Clostridium piliforme*, *Myobia* spp. and *Myocoptes* spp. Autoclaved Enrich-o'Cobs (The Andersons Incorporated) were used as bedding. Cages and bedding were changed weekly. Mice had *ad libitum* access to municipal city water that was sterilized with ultraviolet light. Room temperature was maintained between 21 °C and 23 °C. Ear tags (1005-1, National Band and Tag Co.) were applied to pups at the time of genotyping for identification purposes. All animal procedures were approved by the Mayo Clinic Institutional Animal Care and Use Committee.

Statistical analysis. Prism software was used for statistical analysis and generation of survival, cataract and tumour latency curves. Two-tailed unpaired *t*-tests were used for pairwise significance unless otherwise indicated. log-rank tests were used for survival, cataract and tumour latency curves. For maximum lifespan extension analysis, two-sided Wang–Allison tests were used¹⁴. For consistency in these comparisons, the following denotes significance in all figures: **P* < 0.05, ***P* < 0.01 and ****P* < 0.001. We note that no power calculations were used. Sample sizes were based on previously published experiments where differences were observed. No samples were excluded. Investigators were blinded to allocation during experiments and outcome assessment, except for rare instances where blinding was not possible.

Single-cell preparations and flow cytometry. To determine the cell type origin of senescent cells accumulating in fat, we prepared single cells from iWAT, collected the stromal vascular fraction by centrifugation and labelled the resulting cells with specific cell surface markers for collection of the CD45⁺, endothelial, and progenitor (adipocyte stem cells plus preadipocytes) cell populations by FACS as previously described^{4,35,37}. To quantify progenitor cells, we divided the number of progenitors

recovered from the stromal vascular fraction by the total number of cells in the stromal vascular fraction. Single cell preparations from wounds were prepared in a similar manner. The proportion of GFP⁺ cells in each population was assessed using flow cytometry as described⁴.

Analysis of age-related phenotypes. Bi-weekly checks for cataracts were performed as described⁵. iWAT cell diameter, adipose depot weight, skin thickness, and skeletal muscle diameter measurements were as described⁴. Open field-testing was performed in a 50 cm × 50 cm box and analysed with TopScan software (CleverSys Inc.). Sclerotic glomeruli and blood urea nitrogen assessments were performed as described³⁸. To determine cardiomyocyte cross-sectional area, three sagittal sections of the mid-ventricle separated by 400 µm were stained with periodic acid–Schiff using a kit (Poly Scientific R&D, k098). At least 150 cardiomyocytes in the left ventricular free wall per section were measured using Image J software. Lethal isoproterenol challenges were performed as described³⁸. Parameters of cardiac function were determined with echocardiography using Vevo2100 Imaging System (VisualSonics Inc.) with a 30 mHz transducer. Mice were lightly anaesthetized by isoflurane (0.8–1.5%) with minimal effect on heart rate. Several m-mode recordings of the cardiac parasternal short axis at the level of papillary muscles were made and subsequently analysed. For non-lethal isoproterenol challenge, mice were analysed at baseline (day 0) and subsequently were administered five consecutive days of treatment with 10 mg kg⁻¹ twice daily as described³⁹. Mice were then assessed for alteration in LV mass on day 6. For longitudinal measurements of cardiac structure recordings were acquired in conscious animals. At least three different recordings per animal at each time point were analysed. Rotarod assessments were as previously published⁴⁰. Exercise ability was performed as described⁴. Novel object discrimination tests were performed as described⁴¹. Grip strength was determined as previously published⁴². Gross haematology was assessed by analysing EDTA-treated whole blood using a Hemavet 950 (Drew Scientific Inc.). FACS-based analyses of peripheral blood leukocyte populations were as previously described⁴³. CD3⁺ T lymphocytes were collected from peripheral blood (isolated using CD3 MicroBeads and MACS columns purchased from Miltenyi Biotech) according to manufacturer's instructions. Glucose tolerance was assessed in mice fasted overnight by measuring blood glucose levels before and at time points after an intraperitoneal injection of glucose (1.0 g kg⁻¹). Insulin sensitivity was measured following a 4 h fast by measuring blood glucose levels before and at time points after an intraperitoneal injection of insulin (0.6 mU g⁻¹). Serum Igf1 concentrations were measured by ELISA according to manufacturer's instructions (R&D Systems, MG100). Wound healing assessments were performed as previously described⁴⁴. Phosphotungstic acid haematoxylin (PTAH) staining on formalin-fixed, paraffin-embedded tissue samples was performed as described previously³⁵.

Quantitative PCR. RNA extraction, cDNA synthesis and qRT–PCR analysis of various mouse tissues and CD3⁺ T lymphocytes collected from peripheral blood were performed as described⁵. RNA extraction from cell lines was performed according to manufacturer's instructions (Qiagen RNeasy mini kit). Sequences of primers for *FKBP-Casp8*, *Egfp*, *Ink4a*, *Arf*, *p21*, *Il6*, *Pai1*, *Igfbp2* and *Mmp13* were as previously published⁴. In addition, the following primers were used: *Mmp3* forward 5'-CCTGATGT-TGGTGGCTTC-3', reverse 5'-TC CTGTAGGTGATGTGGGATTTC-3'; *Pparg* forward 5'-TCTTCCATCAC GGAGAGGTC-3', reverse 5'-GATGCACTGCCTATGAGC-AC-3'; *Cebpa* forward 5'-TTGTTTGCTTATCTCGGC-3', reverse 5'-CCAAGAAG-TC GGTGGACAAG-3'; *Il1a* forward 5'-TCAACCAAACATATATATCAGGAT GT GG-3', reverse 5'-CGACTAGGCATACATGTCAAATTTAC-3'; *Tnfa* forward 5'-AGGGTCTGGGCCATAGAAC-3', reverse 5'-CAGCCTCTT CTCATTCCCTG-3'; *Agtr1a* forward 5'-AAGGGCCATTTCCTT-TCT-3', reverse 5'-AACTCACAGAACCTCCAA-3'; *Sur2a* forward 5'-CAATG GAGGCTGTCAGAAC-3', reverse 5'-GGAGCTGACAGACACGAACA-3'; and *Igfbp5* forward 5'-ATACAACCCAGAACGCCAGCT-3', reverse 5'-ACC TGGGCTATGCACTTGATG-3'.

SA-β-Gal staining, electron microscopy and X-ray elemental analysis. For SA-β-Gal staining on kidney cryosections, tissue was embedded in OCT, sectioned at 10 µm thickness, and air-dried. After rehydration in PBS, staining was performed using the Cell Signaling kit (9860) with a 12-min fixation followed by incubating in the staining solution at 37 °C for 12 h. Whole mount SA-β-Gal stainings on fat, kidney and heart were performed using a kit (Cell Signaling), with a 20-min fixation followed by immersing samples in the staining solution at 37 °C for 12 h (iWAT and eWAT) or 48 h (heart and kidney). Detection of X-Gal crystals by transmission electron microscopy was as previously described⁴⁵. Specifically, X-Gal-containing whole mounts were fixed in Trump's fixative at 4 °C for 12 h and routinely processed for OsO₄/lead staining. Images were acquired and quantification performed on a Jeol 1400+ electron microscope with 80 kV acceleration voltage. The authenticity of X-Gal crystals was confirmed by X-ray elemental analysis, whereas the specificity of crystal formation was verified using fat and heart tissue that was not

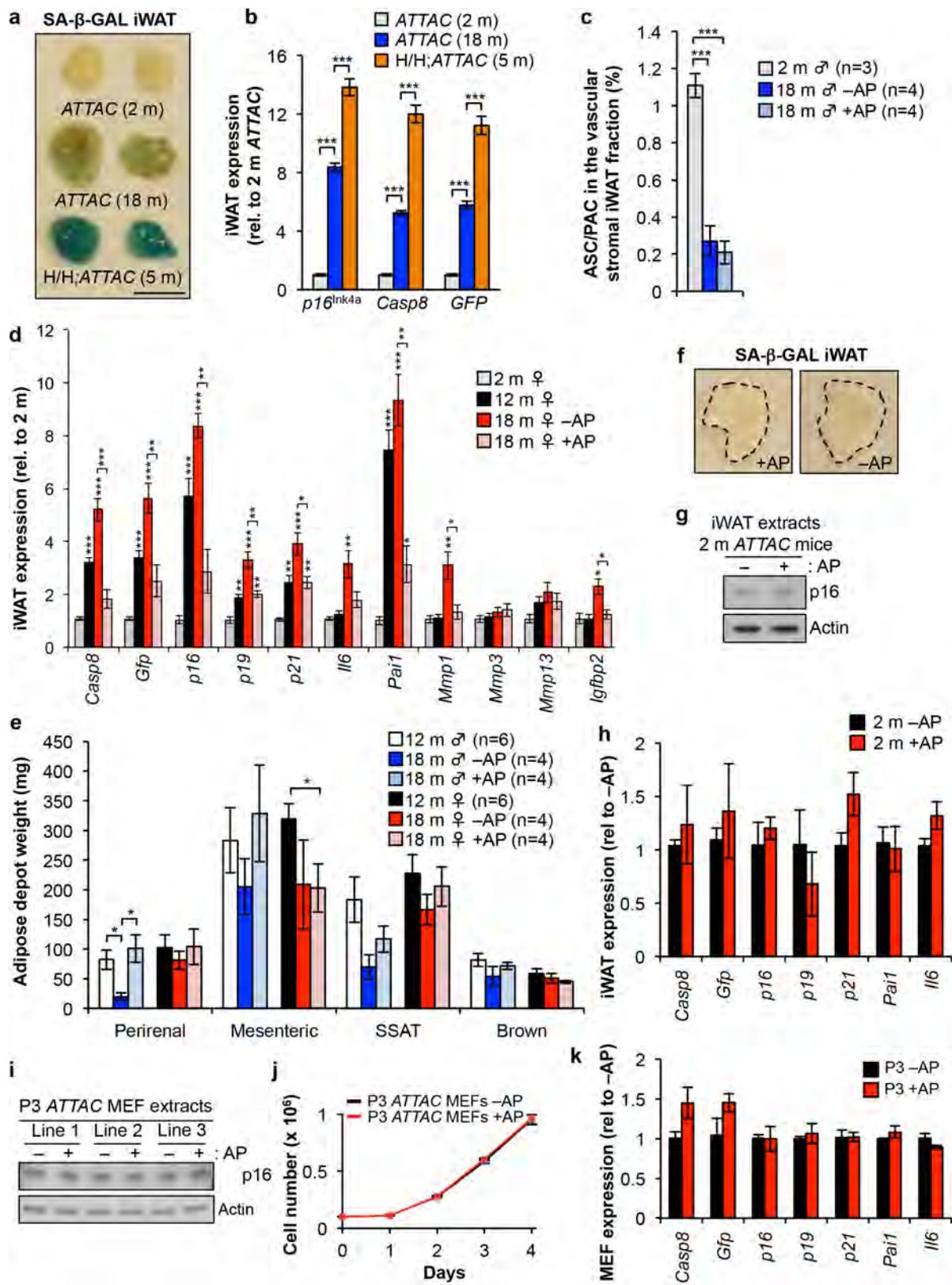
stained for SA- β -Gal. To measure the percentage of X-Gal-crystal-containing cells in kidney sections of AP- or vehicle-treated mice, we screened 5 grids ($>1,500$ cells per grid) per treatment group for cells X-gal-positive cells at $3,000\times$ magnification. Cells with one or more crystals and the total number of cells were counted. iWAT and the visceral pericardium were assessed similarly, with cells with one or more crystals considered to be X-Gal positive. For iWAT, we only observed crystals in stromovascular cells with morphology and perivascular location consistent with adipocyte progenitors and therefore expressed the X-Gal fraction of total cells. More than 500 total fat cells per animal were scored for iWAT ($n=4$ animals per group). Total cells was estimated by extrapolating from the cellularity of five $1,500\times$ fields. Owing to dissection and processing, the serous pericardium was lost for most samples, so the visceral pericardium alone was scored via TEM. Only ciliated epithelial cells stained positive for SA- β -Gal, therefore we expressed the X-Gal positivity of this tissue as percentage of this cell type. The entire visible pericardium on one TEM grid per animal was scored, with four animals per group. For quantitation of SA- β -Gal positive cells in GFP $^+$ and GFP $^-$ cell fractions collected from iWAT, 100 cells were scored per fraction ($n=3$ animals).

Tissue immunofluorescence staining and western blotting. Paraffin-embedded kidney tissue sections ($5\mu\text{m}$) were rehydrated ($2\times 10\text{ min}$ xylene; $2\times 5\text{ min}$ 100% ethanol; $1\times 5\text{ min}$ 95% ethanol; $1\times 5\text{ min}$ 70% ethanol), incubated in protease from *Streptomyces griseus* (Sigma, P6911; 0.75 mg ml^{-1} in Tris buffer, 0.05 M, pH 7.6) for 1 h at 37°C to retrieve antigens, blocked with Rodent Block M (BioCare Medical) for 30 min, and incubated with rabbit anti-Agr1a antibody (Novus Bio, NBP1-77078; 1:250) in antibody diluent (Dako) for 12 h at 4°C . Western blotting on tissue lysates was performed according to standard methods, incubating the nitrocellulose membrane overnight at 4°C with the following antibodies: Agtr1a (as above; 1:750), S6K (Cell Signaling, 2708; 1:1,000), phospho-S6K (Cell Signaling, 9234; 1:1,000), AKT (Cell Signaling, 9272; 1:1,000), and phospho-AKT S473 (Cell Signaling, 9271; 1:1,000). Quantification of p-S6K/S6K and p-AKT S473 /AKT ratios was performed as described 46,47 .

Cell culture. ATTAC MEFs were generated as previously described 4 . Western blotting for p16 INK4a and mouse anti-actin was performed as described 48 . Growth curves were generated as previously described 48 . RNA extraction was done with a Micro RNeasy kit according to manufacturer's instructions (Qiagen). Early passage p16-3MR MEFs 8 were provided by J. Campisi and M. Demaria. Early passage

homozygous p16-FLUC MEFs 49 were provided by C. Burd. MEFs were immortalized by expression of SV40 large T antigen as described 50 . The cell line genotypes were authenticated by PCR genotyping. They were not tested for mycoplasma contamination.

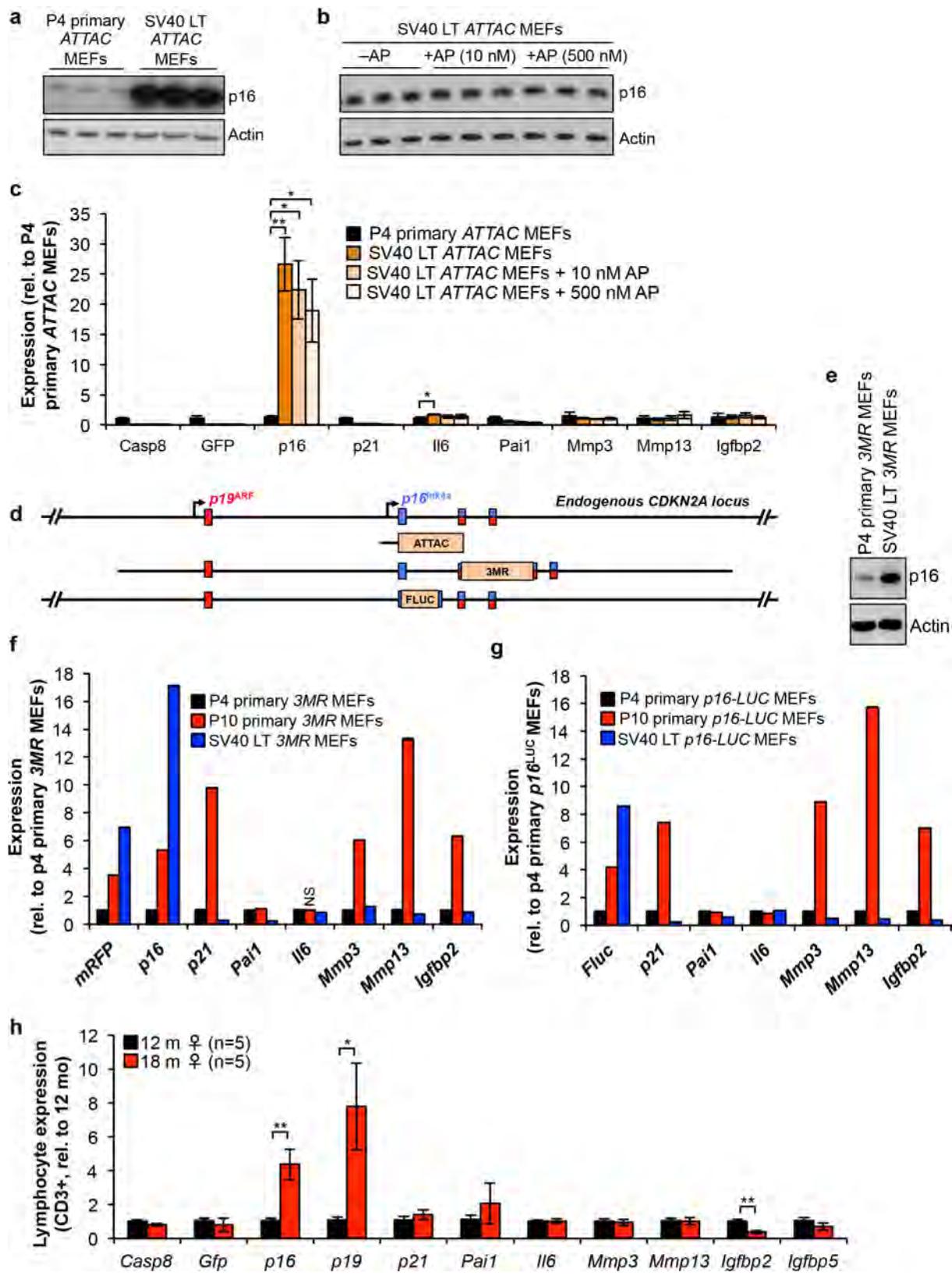
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Extended Data Figure 1 | See next page for figure caption.

Extended Data Figure 1 | ATTAC transgene expression tracks with expression of senescence markers in iWAT and induces apoptosis of senescent cells after AP administration. **a**, Comparative analysis of SA- β -Gal activity in intact iWAT. Scale bar, 0.5 cm. **b**, Analysis of endogenous *Ink4a* and ATTAC transcript SA- β -Gal activity in iWAT by qRT-PCR. H/H denotes *BubR1*^{H/H} mice ($n = 4$ mice per group). **c**, FACS-based quantification of iWAT progenitor cell numbers in 18-month-old ATTAC mice treated with vehicle or AP. ASC, adipocyte stem cells; PAC, preadipocytes. **d**, Expression of the ATTAC transgene and senescence markers in iWAT as determined by qRT-PCR ($n = 4$ mice per group). Asterisks above individual bars denote significant changes to 2-month-old mice; asterisks above brackets denote significant differences between 18-month-old vehicle and AP-treated mice. **e**, Perirenal, mesenteric, subscapular and brown adipose tissue depot weights. SSAT, subscapular adipose tissue. **f**, SA- β -Gal activity in iWAT from 2-month-old ATTAC

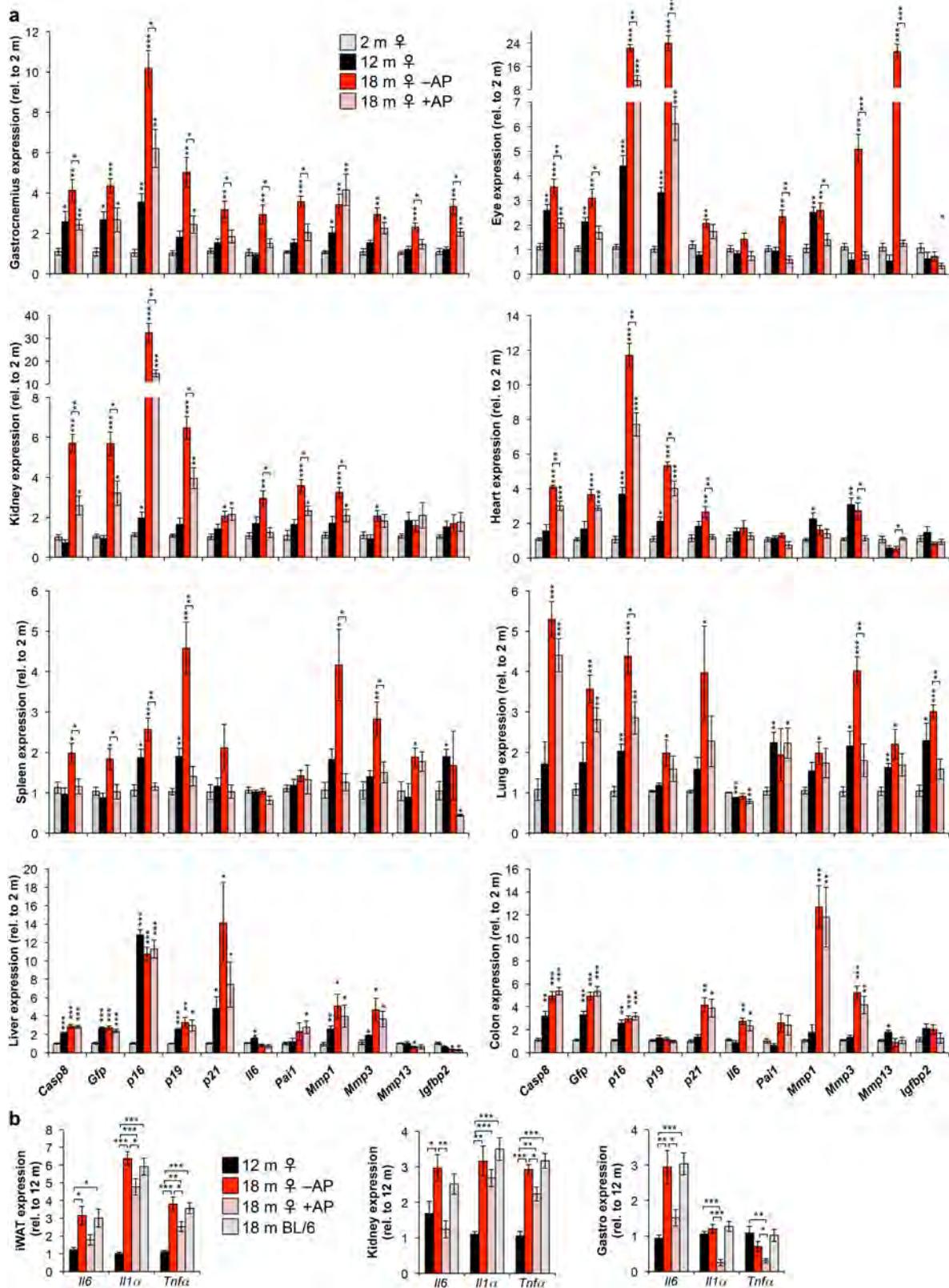
mice treated with vehicle or AP beginning at weaning age. **g**, p16^{Ink4a} levels in iWAT from the mice described in **f**. Actin was used a loading control. **h**, Expression of ATTAC and senescence marker mRNA in the mice described in **f** ($n = 3$ mice per group). **i–k**, Early passage non-senescent ATTAC MEFs express p16^{Ink4a} but are not susceptible to FKBP–Casp8-mediated elimination when cultured in the presence of AP. **i**, Levels of p16^{Ink4a} in passage 3 ATTAC MEFs, with and without AP treatment. **j**, Growth curves of passage 3 ATTAC MEFs ($n = 4$ independently generated MEF lines per group), with or without AP treatment. **k**, Expression of ATTAC and senescence marker mRNA in passage 3 ATTAC MEFs ($n = 3$ independently generated MEF lines per group), with or without AP treatment. Error bars indicate s.e.m. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ (unpaired two-tailed *t*-tests). For gel source data, see Supplementary Fig. 1.



Extended Data Figure 2 | See next page for figure caption.

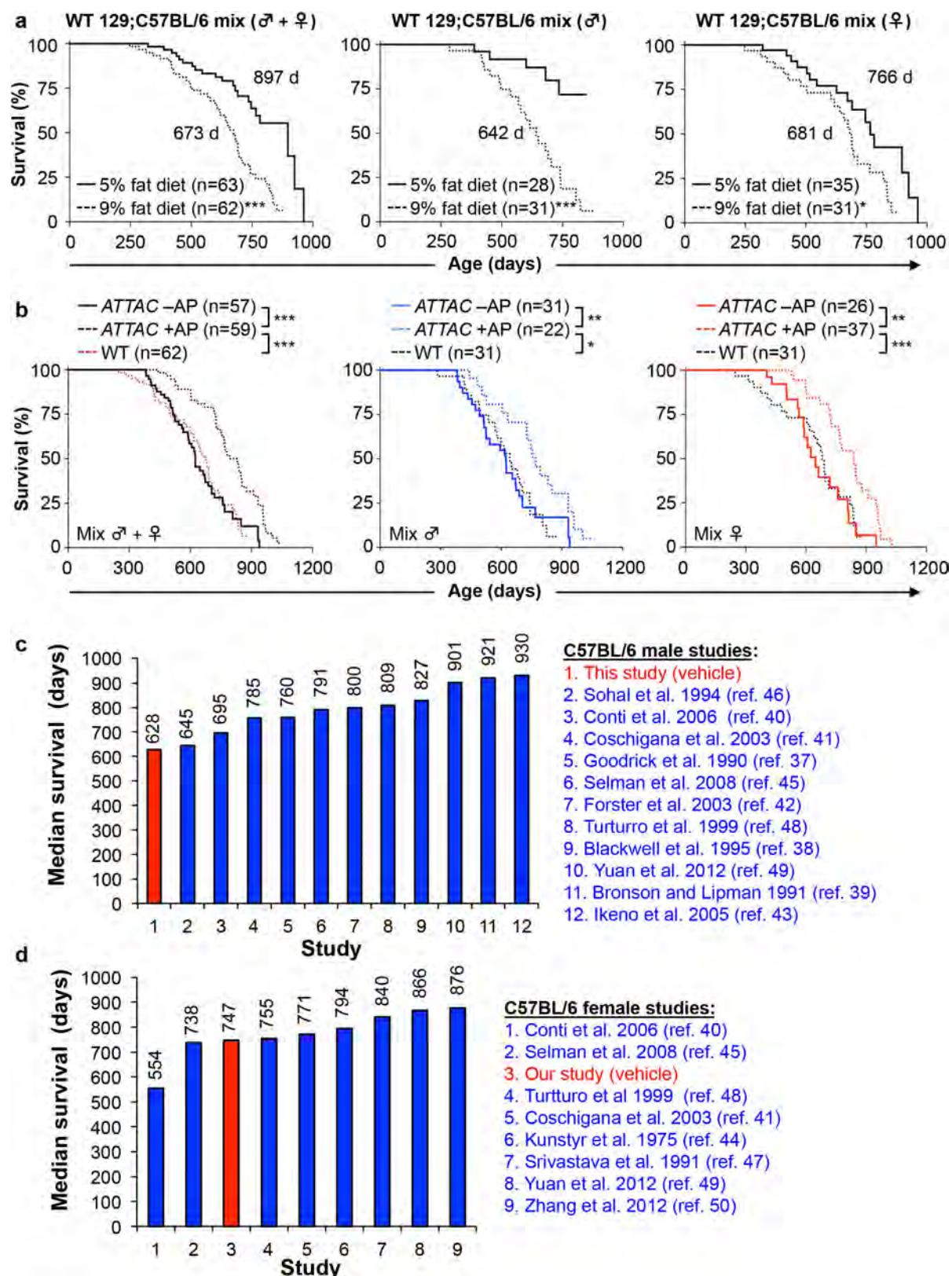
Extended Data Figure 2 | ATTAC lacks promoter elements required for expression in replication-competent cells or aged lymphocytes expressing high levels of endogenous p16^{Ink4a}. **a–c**, SV40 large-T-antigen-immortalized ATTAC MEFs robustly express endogenous p16^{Ink4a} (owing to SV40 large-T-antigen-mediated inactivation of Rb) but fail to engage the ATTAC transgene and are not subject to FKBP–Casp8-mediated elimination. **a**, p16^{Ink4a} protein levels in passage 4 (P4) primary MEFs and MEFs immortalized with SV40 large T antigen. Actin was used as a loading control. **b**, p16^{Ink4a} protein levels in immortalized MEFs treated with vehicle or two concentrations of AP. Actin was used as a loading control. **c**, Expression of ATTAC and senescence marker transcripts in passage 4 primary MEFs, vehicle-treated immortalized MEFs, and AP-treated immortalized MEFs ($n = 3$ independently generated MEF lines per group). **d**, Schematic representation of the endogenous *Ink4a* locus and the various *Ink4a* promoter regions driving ATTAC, 3MR and firefly luciferase (FLUC). ATTAC and p16-3MR mice have 2.6 kb and \sim 50 kb *Ink4a* promoter fragments driving transgene activity, respectively.

p16-FLUC has firefly luciferase knocked into the endogenous *Ink4a* locus, which keeps the entire promoter region intact but ablates p16^{Ink4a} protein expression. **e**, p16^{Ink4a} protein levels in early passage primary and SV40 large-T-antigen-immortalized *p16-3MR* MEFs. **f**, Expression of senescence marker mRNA in early and late passage primary MEFs and SV40 large-T-antigen-immortalized *p16-3MR* MEFs ($n = 1$ independently generated MEF line per group performed in triplicate). **g**, Expression of senescence marker mRNA in early and late passage primary MEFs and SV40 large-T-antigen-immortalized *p16-FLUC* MEFs ($n = 1$ independently generated MEF line per group performed in triplicate). **h**, Expression of ATTAC and senescence markers in CD3⁺ T cells from 12- and 18-month-old ATTAC mice ($n = 5$ mice per group). Error bars indicate s.e.m. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ (unpaired two-tailed *t*-tests). We note that all values in **f** and **g** have $P < 0.05$ compared to passage 4 MEFs, with the exception of the one marked NS for not significant. For gel source data, see Supplementary Fig. 1.



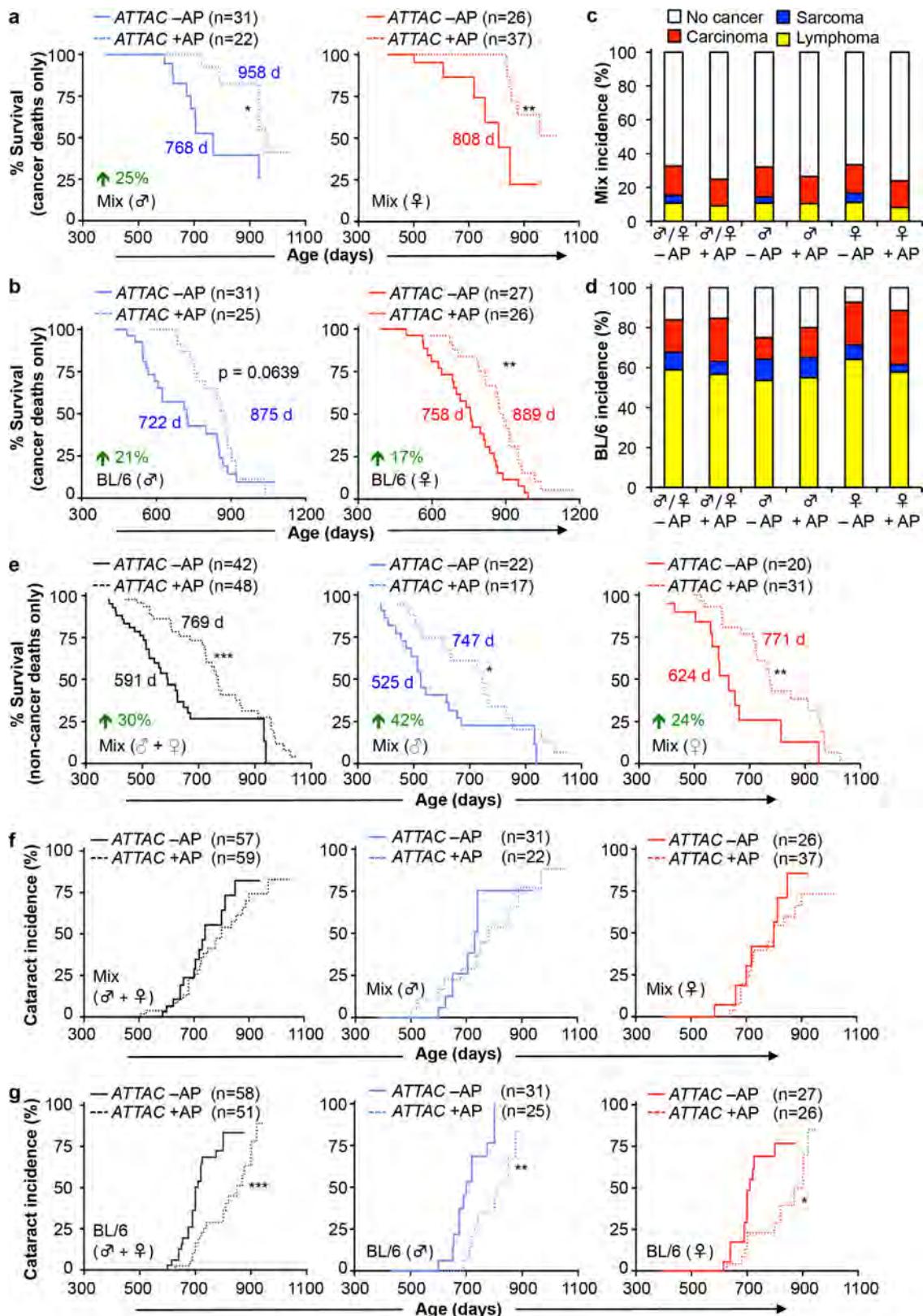
Extended Data Figure 3 | ATTAC-mediated clearance of senescent cells is partial and tissue selective and attenuates expression of inflammation markers. a, Expression of the ATTAC transgene and a senescence marker panel, as determined by RT-PCR, in gastrocnemius, eye, kidney, heart (atria), spleen, lung, liver and colon ($n = 4$ females per group). b, Expression of *Il6*, *Il1α* and *Tnfα* as determined by qRT-PCR in mouse iWAT, kidney and skeletal muscle at different ages ($n = 4$ females per group). *Il6* values are as indicated in Extended Data Fig. 1d (iWAT) and

in a (kidney and gastrocnemius). Expression levels of inflammation markers in unmanipulated 18-month-old C57BL/6 females suggests that repeated vehicle injections were not a source of tissue inflammation. Error bars indicate s.e.m. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ (unpaired two-tailed *t*-tests). Asterisks above individual bars in a denote significant changes to 2-month-old mice; asterisks above brackets denote significant differences between 18-month-old vehicle and AP-treated mice.



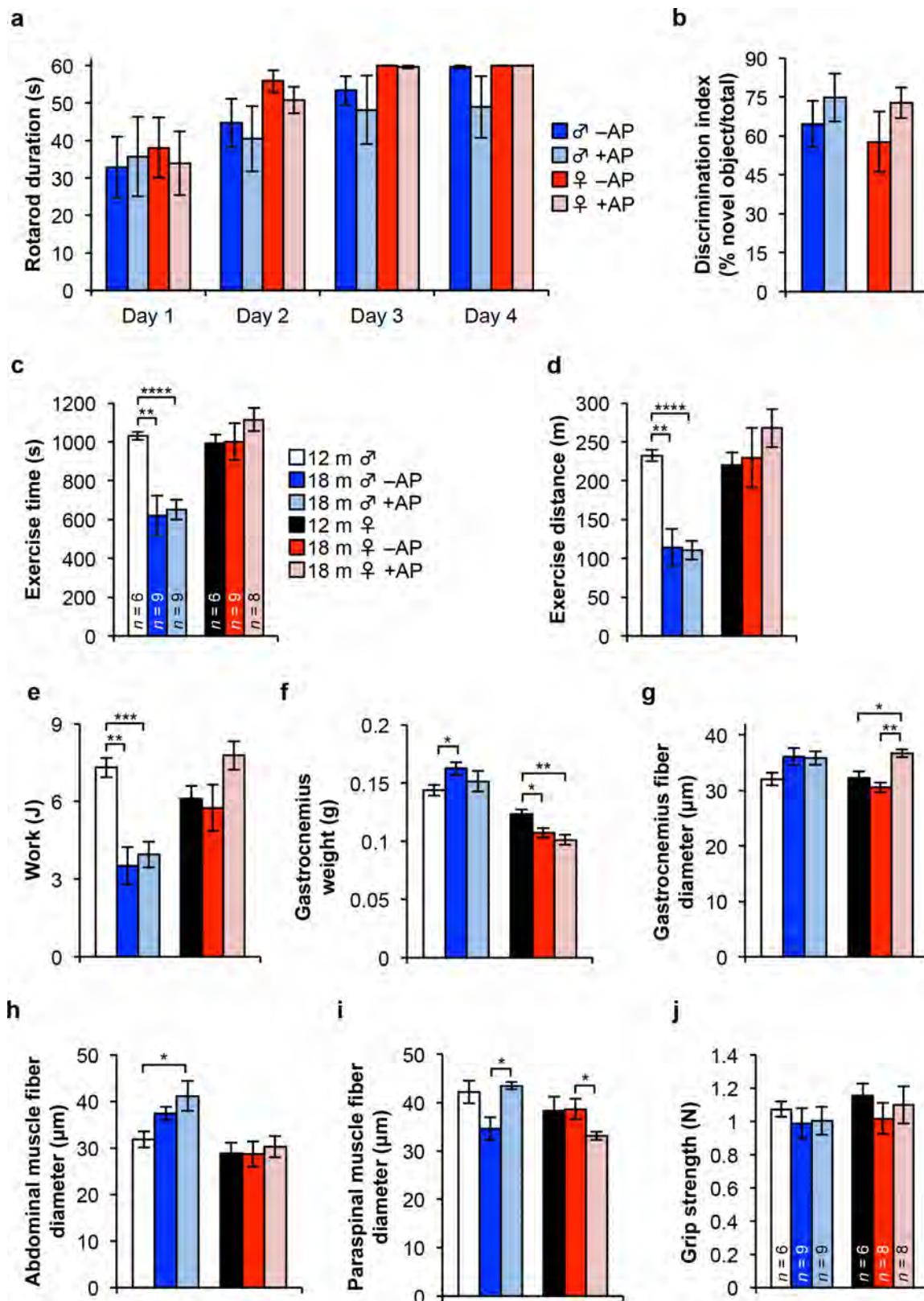
Extended Data Figure 4 | Comparison of lifespans under different diets and housing facilities. **a**, Survival curves of unmanipulated wild-type C57BL/6-129Sv mice fed a 5% versus 9% fat diet. Median lifespan (in days) are indicated. **b**, Survival curves of unmanipulated wild-type C57BL/6-129Sv mice fed a 9% fat diet plotted against those of vehicle-treated (-AP) and AP-treated (+AP) C57BL/6-129Sv-FVB ATTAC mice from Fig. 2b.

These data suggest that the lifespans of vehicle-injected C57BL/6-129Sv-FVB control mice were quite normal for the diet that they were on, and unlikely to be negatively affected by repeated intraperitoneal injections. * $P < 0.01$; ** $P < 0.001$; *** $P < 0.0001$ (log-rank tests). **c, d**, Median survival data of unmanipulated C57BL/6 male (**c**) and female (**d**) mice from various laboratories for comparison to the results obtained from our facility.



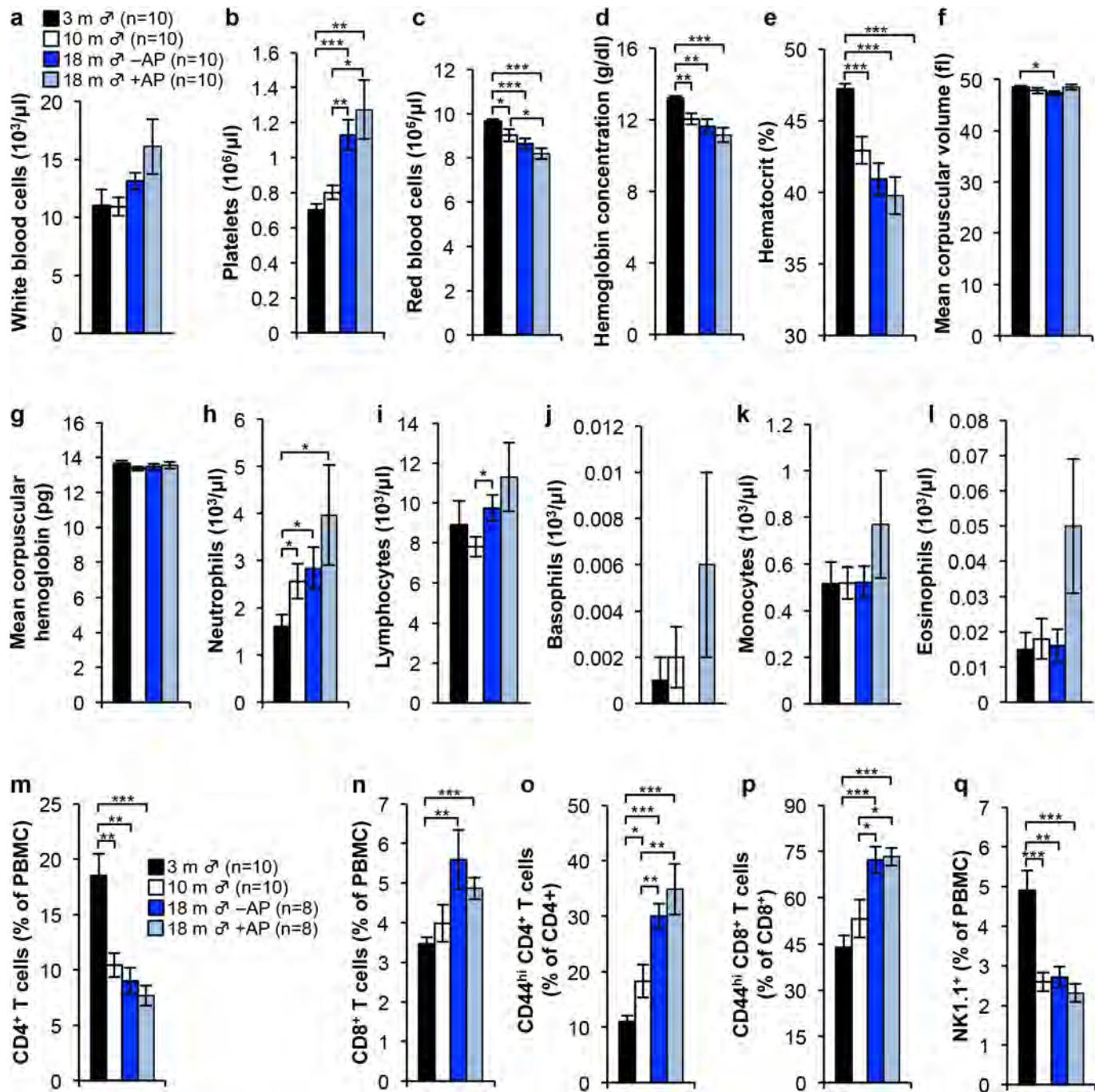
Extended Data Figure 5 | Senescent cell clearance delays tumour and cataract formation. **a, b,** Survival curves of mixed (a) and C57BL/6 (b) ATTAC mice dying of cancer (mice that had an overt tumour at time of death; only mice with lymphomas, sarcomas and carcinomas were included). Median survival (in days) and percentage increase are indicated. **c, d,** Incidence of macroscopically detectable neoplasms (lymphomas, sarcomas and carcinomas) at time of death in mixed (c) and C57BL/6

(d) ATTAC mice from survival cohorts. **e,** Survival curves of C57BL/6-129Sv-FVB mice dying without cancer (mice that had an overt tumour at time of death, including lymphoma, sarcoma and/or carcinoma, were excluded). Median survival (in days) and percentage increase are indicated. **f, g,** Cataract incidence for mixed (f) and C57BL/6 (g) ATTAC mouse cohorts. *P < 0.05; **P < 0.01; ***P < 0.001 (log-rank tests).



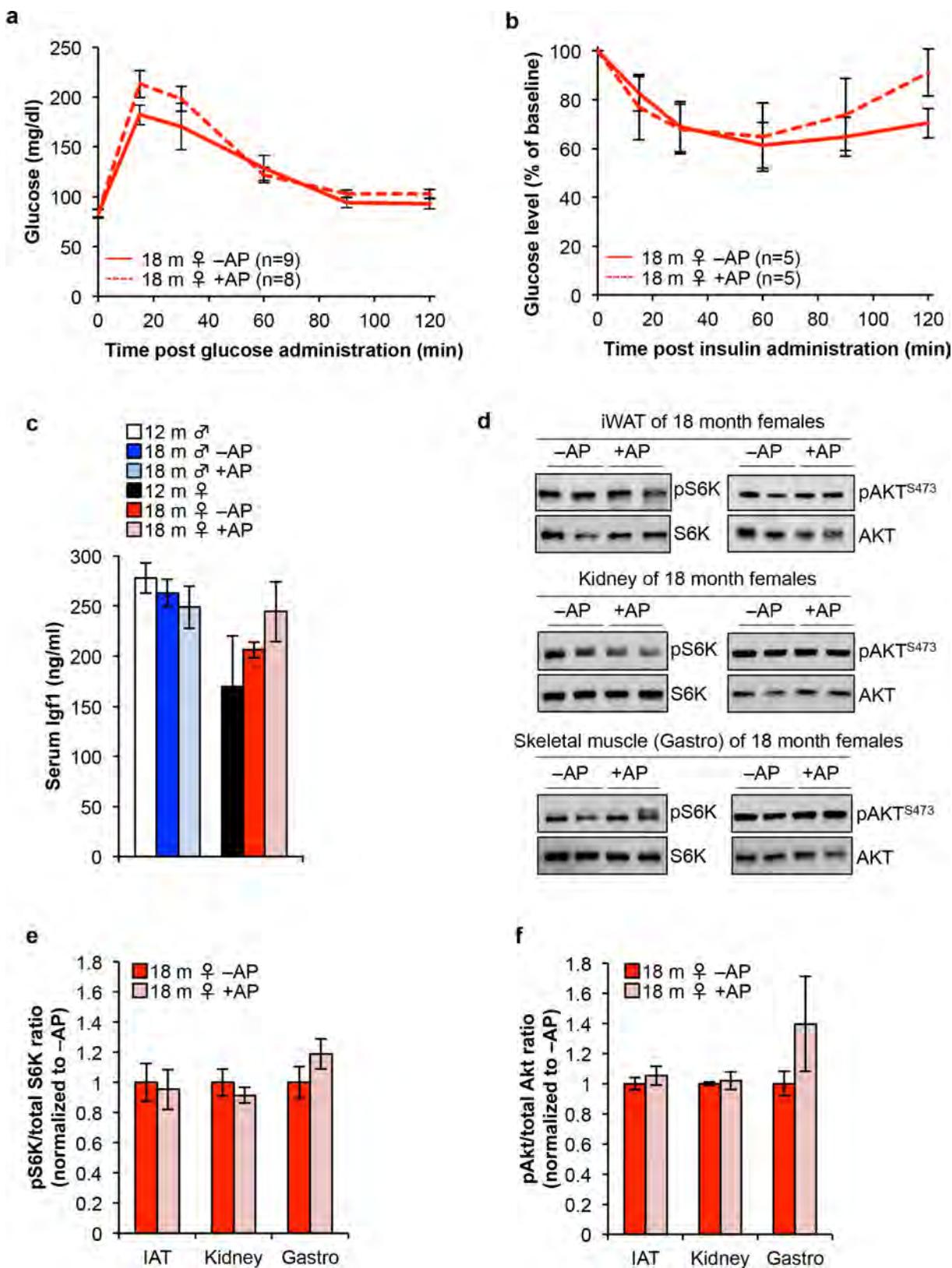
Extended Data Figure 6 | Senescent cell clearance does not affect coordination, memory or exercise ability of 18-month-old ATTAC mice. **a**, Time spent balanced during a fixed speed rotarod test for 18-month-old ATTAC mice ($n = 6$ male and 8 female mice per group). **b**, Novel object investigation test. The percentage of investigations of a novel object divided by the total investigations is graphed. Key and animal numbers are as indicated in **a**. **c–e**, Time-to-exhaustion (**c**), distance (**d**) and work (**e**) during a treadmill exercise test. Animal numbers are as

indicated in **c**. **f**, Gastrocnemius muscle weight of ATTAC mice ($n = 6$ 12-month-old males and females; $n = 4$ 18-month-old –AP males and females; $n = 4$ 18-month-old +AP males and females). **g–i**, Myofibre diameter measurements on isolated gastrocnemius (**g**), abdominal (**h**) and paraspinal muscle (**i**). Animal numbers are as indicated in **f**. **j**, Analysis of forelimb grip strength of ATTAC mice. Error bars indicate s.e.m. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ (unpaired two-tailed *t*-tests).



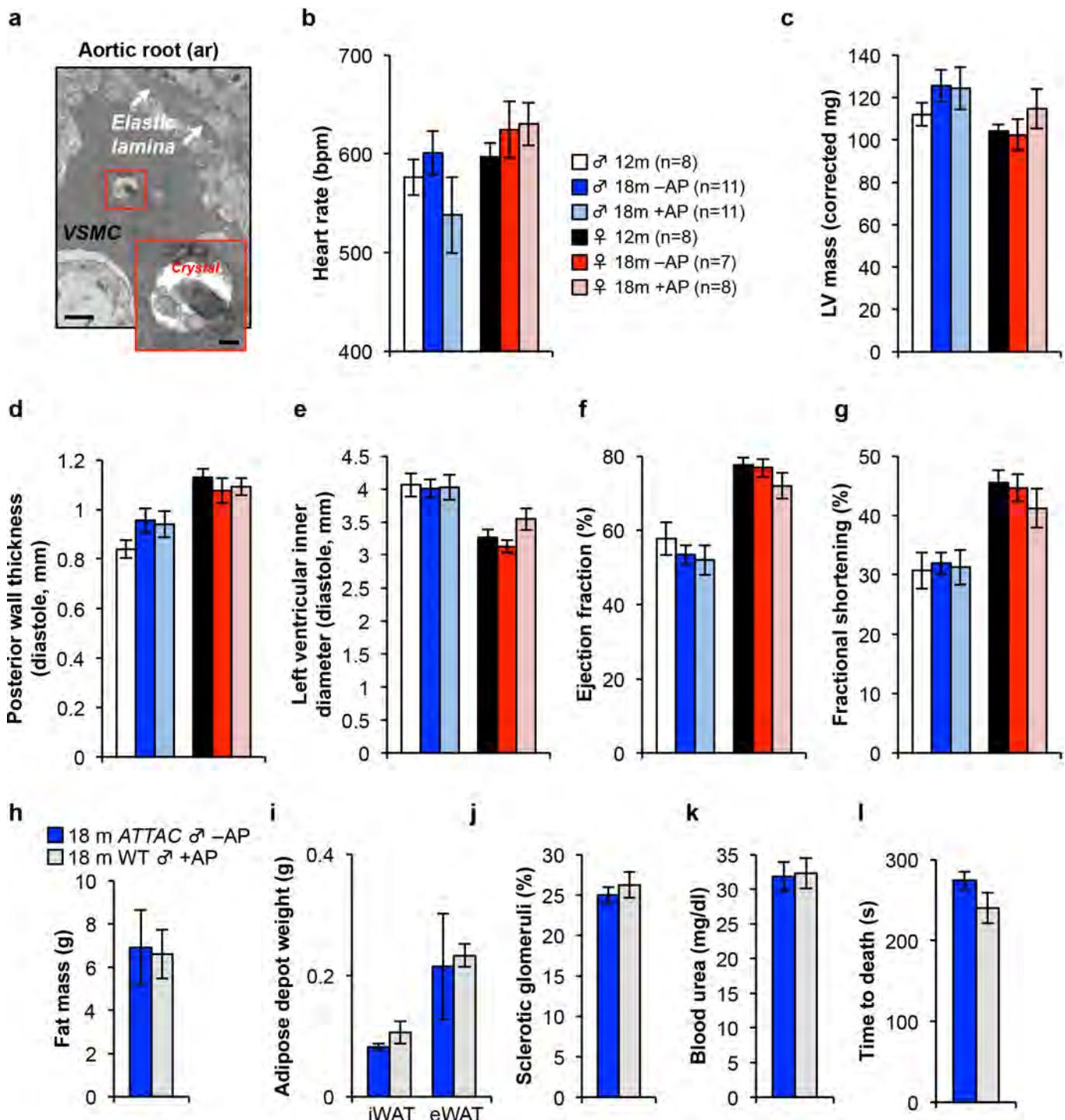
Extended Data Figure 7 | Senescent cell clearance has no effect on haematological parameters and age-related changes in leukocyte populations. a–l, Haematology results of 3- and 10-month-old untreated ATTAC C57BL/6 mice and 18-month-old vehicle- and AP-treated ATTAC C57BL/6 mice. White blood cell count (a), platelet count (b), red blood cell count (c), haemoglobin concentration (d), haematocrit (e), mean corpuscular volume (f), mean corpuscular haemoglobin (g), neutrophils (h), lymphocytes (i), basophils (j), monocytes (k) and eosinophils (l).

m–q, Assessment for leukocyte subpopulations in 3- and 10-month-old untreated ATTAC C57BL/6 mice and 18-month-old vehicle- and AP-treated ATTAC C57BL/6 mice. CD4⁺ T cells (percentage of peripheral blood mononuclear cells, PBMC) (m), CD8⁺ T cells (percentage of PBMC) (n), CD44^{hi} CD4⁺ T cells (percentage of CD4⁺) (o), CD44^{hi} CD8⁺ T cells (percentage of CD8⁺) (p), and NK1.1⁺ cells (percentage of PBMC) (q). Error bars indicate s.e.m. *P<0.05; **P<0.01; ***P<0.001 (unpaired two-tailed t-tests).



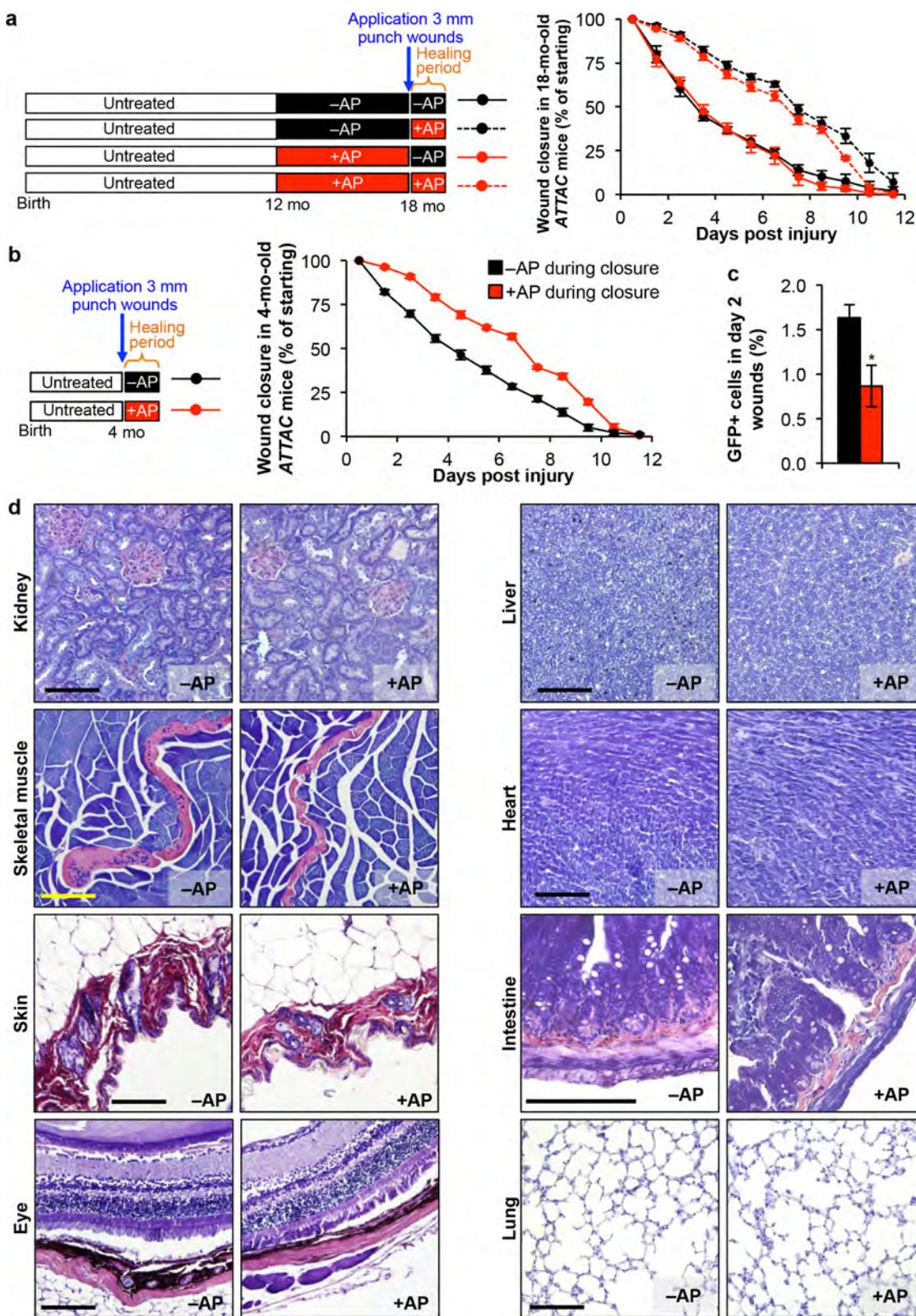
Extended Data Figure 8 | Senescent cell removal does not affect somatotropic axis signalling *in vivo*. **a**, Glucose levels following intraperitoneal glucose administration after an overnight fast in 18-month-old vehicle- and AP-treated ATTAC C57BL/6 females. **b**, Normalized glucose levels after intraperitoneal insulin administration following a 4-h fast in 18-month-old vehicle- and AP-treated ATTAC C57BL/6 females. **c**, Serum Igf1 levels in ATTAC C57BL/6 mice ($n=4$ mice of each group). **d**, Representative western blots for phospho-S6K,

total S6K, phospho-AKT^{S473} and total AKT in iWAT, kidney and skeletal muscle tissue lysates from 18-month-old vehicle- and AP-treated ATTAC C57BL/6 females. **e**, Quantification of phospho-S6K to total S6K ratio in blots from **d**, $n=4$ mice of each group. **f**, Quantification of phospho-AKT^{S473} to total AKT ratio in blots from **d**, $n=4$ mice of each group. Error bars indicate s.e.m. No statistically significant differences were observed in **a–c**, **e** and **f** using unpaired two-tailed *t*-tests. For gel source data, see Supplementary Fig. 1.



Extended Data Figure 9 | Senescent cell clearance does not alter cardiac morphology and function in ‘resting’ mice and AP treatment has no effect on healthspan of mice lacking the ATTAC transgene. **a**, Electron micrographs of X-Gal crystal containing cells in the aortic root. VSMC, vascular smooth muscle cell. Scale bars, 1 μm (main panel) and 200 nm (inset). **b–g**, Echocardiography measurements of heart rate (**b**), left ventricular mass (**c**), posterior wall thickness (**d**), left ventricular inner diameter (**e**), ejection fraction (**f**), and the fractional shortening of the heart (**g**) in 12-month-old untreated mice and 18-month-old ATTAC mice treated with vehicle or AP. **h**, Fat mass ($n=9$ mice per group). 18-month-old

ATTAC vehicle-treated mouse values are the same as indicated in Fig. 1. **i**, iWAT and eWAT depot weight ($n=4$ mice per group). 18-month-old ATTAC vehicle-treated mouse values are the same as indicated in Fig. 1. **j, k**, Kidney sclerosis (**j**) and blood urea levels (**k**) ($n=4$ mice per group). 18-month-old ATTAC vehicle-treated mouse values are the same as indicated in Fig. 4. **l**, Time to death after isoproterenol administration ($n=4$ mice per group). 18-month-old ATTAC vehicle-treated mouse values are the same as indicated in Fig. 5. Error bars indicate s.e.m. No statistically significant differences were observed using unpaired two-tailed *t*-tests.



Extended Data Figure 10 | Effect of senescent cell clearance on wound healing and tissue fibrosis. **a**, Closure of 3-mm punch biopsy wounds in 18-month-old ATTAC females after treatment with vehicle or AP for 6 months and if drug treatment was stopped 2 days before skin puncture or continued during wound closure ($n = 6$ wounds for -AP; -AP and +AP; -AP and $n = 10$ wounds for -AP; +AP and +AP; +AP). AP administration during the wound healing process significantly attenuates the rate of wound closure independently of whether senescent cell removal had occurred before wounding. **b**, Closure of 3-mm punch biopsy wounds in 4-month-old ATTAC females after treatment with vehicle or AP following

wounding ($n = 10$ wounds per group). Similar to 18-month-old mice, AP administration during the wound healing process dramatically attenuated the rate of wound closure. **c**, Quantification of total GFP⁺ cells isolated from 3-mm punch biopsy wounds of 4-month-old mice two days into the wound healing process treated with vehicle (black) or AP (red, $n = 3$ mice per group). **d**, PTAH-stained tissue sections from 18-month-old ATTAC mice for detection of fibrosis. Scale bars, 100 μ m. Error bars indicate s.e.m. Mice receiving AP during the healing process in **a** and **b** are significantly different from those treated with vehicle from day 1.5 to day 9.5. * $P < 0.05$ (unpaired two-tailed t -tests).

Author: Please check the wording of the following statement, which will appear online only.

J.M.v.D. and D.J.B. are inventors on patents licensed to Unity Biotechnology by Mayo Clinic and J.M.v.D. is a co-founder of Unity Biotechnology.

SUPPLEMENTARY TEXT

Selectivity of *ATTAC*-mediated cell clearance

ATTAC uses the first 2,617 base pairs of the endogenous mouse *p16^{Ink4a}* gene promoter to drive an *FKBP-Caspase 8* “suicide” gene and *EGFP* expression in senescent cells. This relatively small fragment lacked distal regulatory elements of the endogenous *p16^{Ink4a}* gene and was selected because of its high transcriptional activity in senescent relative to non-senescent cells¹. Our earlier work in BubR1 progeroid mice demonstrated that only the tissues showing elevated expression of *p16^{Ink4a}* and other senescence markers (fat, skeletal muscle and eye) have elevated levels of *FKBP-Casp8* and *GFP* transcripts². Upon AP treatment, these tissues selectively showed an attenuated functional decline and decreased transcript levels of *FKBP-Casp8*, *GFP*, *p16^{Ink4a}*, and senescence markers, indicating that *ATTAC* targets senescent cells for elimination.

Robust induction of endogenous *p16^{Ink4a}* has also been observed outside the context of cellular senescence, for instance upon disruption of Rb, a frequent event in human cancers that drives neoplastic growth. To determine whether *ATTAC* might be co-activated and mediate cell death in this context, we employed SV40 large T antigen, a well-established inhibitor of Rb known to induce robust *p16^{Ink4a}* gene expression. A lentiviral expression system was used to express constitutively SV40 large T antigen in primary *ATTAC* MEFs. Western blot analysis confirmed that the endogenous *p16^{Ink4a}* gene was hyperactive in these MEFs (Extended Data Fig. 2a). However, we observed no co-induction of the *ATTAC* transgene (see Casp8 and GFP expression in revised Extended Data Fig. 2c), which correlated with a lack of induction of senescent cell markers. Furthermore, SV40 large T immortalized MEFs were resistant to AP-induced apoptosis (Extended Data Fig. 2b, c). Together, these data suggest that *ATTAC* is lacking *p16^{Ink4a}* promoter elements critical for driving *p16^{Ink4a}* transcription in the context of Rb loss, and is thus unlikely to eliminate cancer cells in which Rb is perturbed.

We repeated the above studies in MEF lines derived from *p16^{Ink4a}*-LUC³ and 3MR mice⁵. The former MEFs are homozygous for a firefly luciferase knock-in at the endogenous *p16^{Ink4a}* locus and the latter MEFs contain a randomly inserted single copy of a bacterial artificial chromosome that spans the murine *Cdkn2a* locus and has a 3MR trimodal reporter gene (generating a fusion protein of Renilla luciferase, mRFP, and herpes simplex virus 1 thymidine kinase) inserted into *p16^{Ink4a}* exon 2 (see Extended Data Fig. 2d for a schematic representation of the differences in these models from *ATTAC*). In contrast to *ATTAC* MEFs, both *p16^{Ink4a}*-LUC and 3MR MEFs induced transgene expression upon inactivation of Rb by SV40 LT antigen (Extended Data Fig. 2f and g). These data confirmed that induction of *p16^{Ink4a}* in non-senescent cells in the setting of Rb disruption depends on a *p16^{Ink4a}* promoter element located outside of the 2617 bp promoter fragment of *ATTAC*.

ATTAC was also not induced in peripheral blood T lymphocytes that robustly engage endogenous *p16^{Ink4a}* with aging without concomitant expression of multiple senescence

markers^{4,5} (Extended Data Fig. 2h), further implying that transgene induction is quite selective for senescence. However, these limited analyses certainly do not exclude the possibility that other *p16^{Ink4a}*-positive non-senescent cells engage *ATTAC* and die upon AP exposure. In the manuscript, we, therefore, referred to the cells eliminated by *ATTAC* as *p16^{Ink4a}*-positive cells rather than *p16^{Ink4a}*-positive senescent cells.

Lifespan and healthspan studies (supplementary information and discussion)

The central goal of this study was to explore the biological impact of senescent cells on health and lifespan, a longstanding unaddressed question. This study is a logical follow-up to our study that demonstrated a deleterious role for *p16^{Ink4a}*-positive senescent cells in premature aging phenotypes of progeroid BubR1 hypomorphic mice². It is well established that lifespan and healthspan are very sensitive to very subtle manipulations. For example, minor changes in husbandry conditions or diet can have significant effects within the same animal facility. Furthermore, median lifespans of C57BL/6 mice (Extended Data Fig. 4c, d) and other mouse strains vary tremendously between test sites (up to 25–30%), even in settings where great effort is made to unify husbandry conditions across mouse facilities, such as the National Institutes of Aging (NIA) Interventions Testing Program (ITP)^{6,7}. Thus, instead of a narrowly defined optimal absolute lifespan, individual mouse strains seemingly have an optimal lifespan range that takes into consideration subtle differences in husbandry conditions as well as undefined, and thus uncontrollable, site-specific factors. With regards to husbandry conditions, our lifespan studies were conducted according to standard conditions (for details see methods section).

Lifespan and healthspan studies should ideally be carried out while exposing the animals to as little stress as possible⁸. For instance, the ITP prefers drug delivery via food or water over methods that require extensive animal manipulation such as repetitive injection⁸. Our approach for removal of senescent cells from transgenic *ATTAC* mice requires repeated administration of AP20187, which is an unstable compound that needs to be supplied by intraperitoneal (IP) injection (twice a week). It should therefore be emphasized that the intervention and control mice in our study were exposed to a greater frequency of manipulation stress than is typical in conventional longevity studies. In C57BL/6 *ATTAC* control males, repeated IP-injection of vehicle seemed to impact negatively the lifespan, as their lifespan is short of the lifespan range for unmanipulated C57BL/6 mice (see Extended Data Fig. 4c). In contrast, no such negative impact was observed in the corresponding female cohort because the lifespan of vehicle-injected C57BL/6 *ATTAC* females was within the normal range compared to eight other test sites (Extended Data Fig. 4d). Importantly, although vehicle-treated C57BL/6 *ATTAC* males lived shorter than unmanipulated C57BL/6 males, the primary cause of death, development of malignant tumors, remains unchanged. As is the case for unmanipulated C57BL/6 males, ~75–80% of vehicle-treated C57BL/6 *ATTAC* males have lymphomas, sarcomas or carcinomas at the time of death, without significant changes in tumor incidence and spectrum compared to AP-treated C57BL/6 *ATTAC* males, whose lifespan is extended to well into the normal range for unmanipulated C57BL/6 males. Based on these data, we believe the most plausible explanation for the shortened lifespan of vehicle-treated C57BL/6 *ATTAC* males is that repeated injections accelerate the progression of the neoplastic lesions that naturally

develop in this strain, causing the animals to die at an earlier than normal age. Consistent with this idea, several laboratories have demonstrated that repetitive stress can accelerate tumorigenesis in mice⁹⁻¹¹.

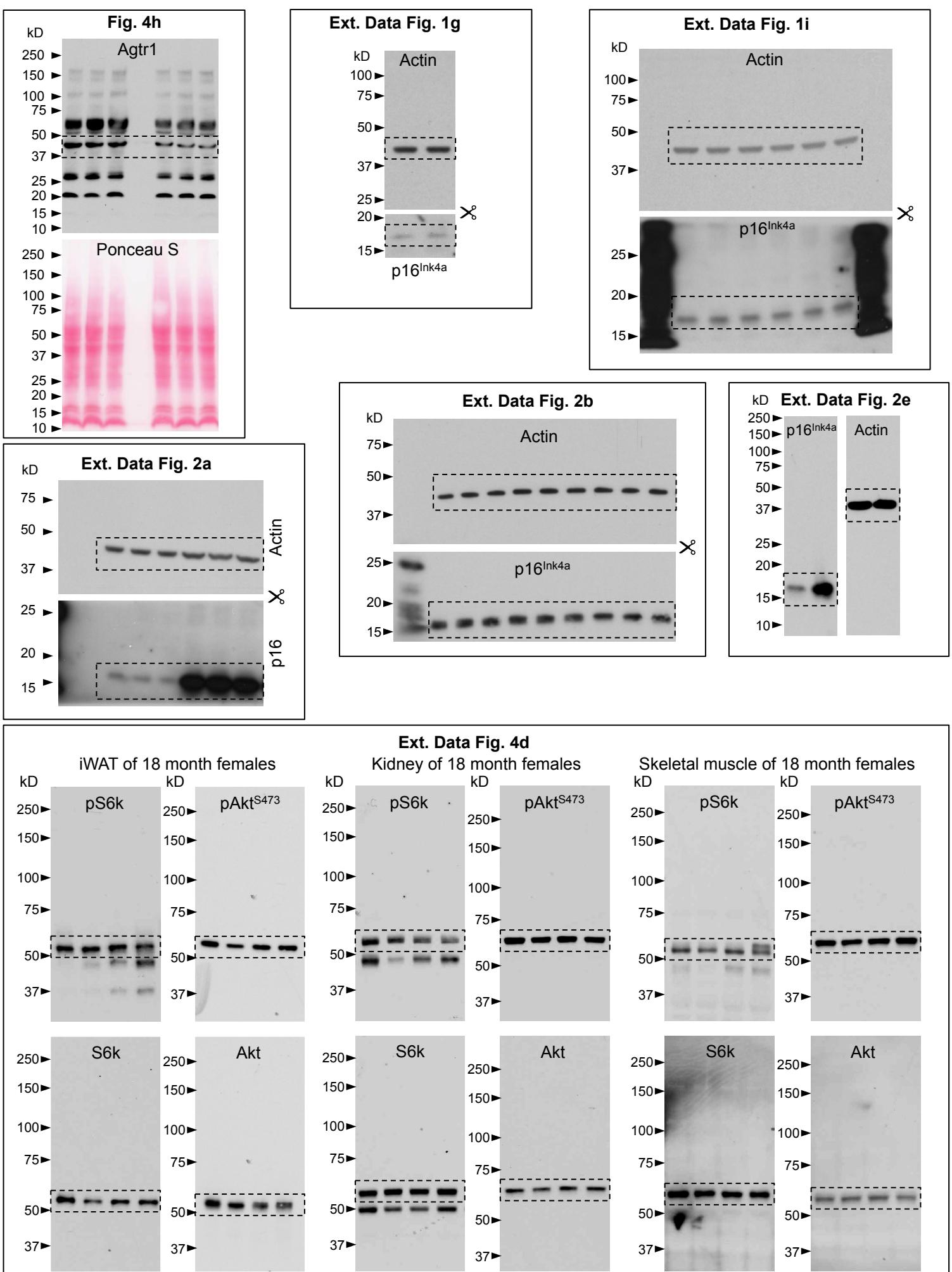
The diet used in the C57BL/6 *ATTAC* study consisted of 5% fat, which is the standard amount of dietary fat content used in lifespan studies. We fed mice of the C57BL/6-129Sv-FVB *ATTAC* study a diet containing 9% fat. Separate lifespan studies ongoing in the lab using unmanipulated wildtype mice of a similar genetic background (C57BL/6-129Sv) revealed that mice on this diet have a 25% shorter lifespan than those on a standard diet containing 5% fat (Extended Data Fig. 4a). Furthermore, these studies suggested that vehicle-treated C57BL/6-129Sv-FVB *ATTAC* mice on 9% fat had a median lifespan that is normal for this diet (Extended Data Fig. 4b): the median lifespans of vehicle-injected C57BL/6-129Sv-FVB *ATTAC* mice were nearly identical to unmanipulated wildtype C57BL/6-129Sv hybrid mice for both males and females. These data indicate that the lifespan of our vehicle-injected C57BL/6-129Sv-FVB control mice is normal for the diet that they were on, and that the 27% lifespan extension observed in AP-treated animals is not just bringing the lifespan for the strain back to normal but an actual lifespan extension for hybrid mice fed a 9% fat diet.

Our experimental system has limitations with regards to killing senescent cells, in that clearance of *p16^{Ink4a}*-positive cells by the *ATTAC* system was partial and tissue/organ selective. Possible explanations include bioavailability and volume of distribution of the drug (e.g. kidney), the level of transgene expression on a per cell basis, expression of anti-apoptotic proteins on a per cell basis, and other currently unknown effects. Therefore, lifespan extensions observed with the *ATTAC* model may well underestimate the effects of more efficient senescent cell clearance. It is important to keep in mind that this is different from lifespan studies using approaches that involve genetic, dietary or pharmacological interventions, which unlike our system, impact virtually all cells of the animal.

The aging field is now broadly recognizing that “normal aging” and “normal lifespan” are not single entities or reference values. There is an evolving understanding of “aging” by the research community and how to best use lifespan and healthspan measures as indices of this process¹². Lifespan, in particular an increase in both mean and maximum longevity, has historically been the method through which an intervention has been deemed successful in “altering aging”^{12, 13}. Interpretation of interventions that increase health and lifespan in terms of “slowing aging” is now more and more recognized as a highly complicated matter and a topic of continued debate in the field. Rather than speaking imprecisely about interventions being “anti-aging”, they should instead be described as ameliorating specific age-related declines under defined conditions. Therefore, in the current study, we sought to investigate the role of senescent cells in a variety of robust, reproducible age-related changes. These include the age-associated increases in cancer, glomerulosclerosis, lipoatrophy, and cardiomyocyte hypertrophy, and decreases in cardiac stress resilience, spontaneous activity and exploratory behavior, all of which are strongly delayed by *p16^{Ink4a}*-positive cell clearance. Importantly, these beneficial effects appear to be independent of genetic background, sex or diet.

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Supplementary Figure 1: Full scans of Western blot data presented in Fig. 4h, Extended Data Fig. 1g, i, Extended Data Fig. 2a, b, e, and Extended Data Fig. 4d. Highlighted are the areas shown in main figures.