

Calorie restriction in humans inhibits the PI3K/AKT pathway and induces a younger transcription profile

Evi M. Mercken,^{1†} Seth D. Crosby,^{2†} Dudley W. Lamming,^{3,4,5,6,7} Lellean JeBailey,⁸ Susan Krzysik-Walker,⁹ Dennis T. Villareal,¹⁰ Miriam Capri,^{11,12} Claudio Franceschi,^{11,12} Yongqing Zhang,¹³ Kevin Becker,¹³ David M. Sabatini,^{3,4,5,6,7} Rafael de Cabo¹ and Luigi Fontana^{10,14,15}

¹Laboratory of Experimental Gerontology, National Institute on Aging, National Institutes of Health, Baltimore, MD 21224, USA

²Department of Genetics, Washington University School of Medicine, St. Louis, MO 63108, USA

³Whitehead Institute for Biomedical Research, Cambridge, MA 02142, USA

⁴Department of Biology, Massachusetts Institute of Technology (MIT), Cambridge, MA 02139, USA

⁵Howard Hughes Medical Institute, MIT, Cambridge, MA 02139, USA

⁶Broad Institute of Harvard and MIT, Seven Cambridge Center, Cambridge, MA 02142, USA

⁷The David H. Koch Institute for Integrative Cancer Research at MIT, Cambridge, MA 02139, USA

⁸GeneGo Inc., St. Joseph, MI 49085, USA

⁹Laboratory of Clinical Investigation, National Institute on Aging, National Institutes of Health, Baltimore, MD 21224, USA

¹⁰Division of Geriatrics and Nutritional Science, Washington University School of Medicine, St. Louis, MO 63108, USA

¹¹CIG - Interdepartmental Centre "Galvani", University of Bologna- ALMA MATER STUDIORUM, Bologna 40126, Italy

¹²Department of Experimental, Diagnostic and Specialty Medicine, University of Bologna- ALMA MATER STUDIORUM, Bologna 40126, Italy

¹³Gene Expression and Genomics Unit, National Institute on Aging, National Institutes of Health, Baltimore, MD 21224, USA

¹⁴Department of Medicine, Salerno University Medical School, Salerno 84081, Italy

¹⁵CEINGE Biotechnologie Avanzate, Napoli 80145, Italy

Summary

Caloric restriction (CR) and down-regulation of the insulin/IGF pathway are the most robust interventions known to increase longevity in lower organisms. However, little is known about the molecular adaptations induced by CR in humans. Here, we report that long-term CR in humans inhibits the IGF-1/insulin pathway in skeletal muscle, a key metabolic tissue. We also demonstrate that CR induces dramatic changes of the skeletal muscle transcriptional profile that resemble those of younger individuals. Finally, in both rats and humans, CR evoked similar responses in the transcriptional profiles of skeletal muscle. This common signature consisted of three key pathways typically associated with longevity: IGF-1/insulin signaling, mitochondrial biogenesis, and

inflammation. Furthermore, our data identify promising pathways for therapeutic targets to combat age-related diseases and promote health in humans.

Key words: caloric restriction; human; insulin/IGF-1 signaling; skeletal muscle.

Introduction

Caloric restriction (CR) without malnutrition and inhibition of the insulin/IGF-1 signaling are the most robust and reproducible interventions for extending lifespan and preventing or delaying age-related disease in a variety of species (Anderson & Weindruch, 2007; Kennedy *et al.*, 2007; Piper & Bartke, 2008). Aging was believed to be the consequence of the inevitable wear and tear process, but in 1993, Kenyon and her associates published the first paper indicating that the inhibition of the insulin/IGF-1/FOXO pathway dramatically extends lifespan in worms (Kenyon *et al.*, 1993). Since then, accumulating data have shown that this pathway is evolutionarily conserved and that dietary and genetic manipulations of the insulin/IGF-1/FOXO pathway extend lifespan in rodents as well (Kenyon *et al.*, 1993; van Heemst *et al.*, 2005; Kennedy *et al.*, 2007; Piper & Bartke, 2008). Moreover, evidence derived from exceptionally long-lived people also supports a role for the IGF signaling pathway in human longevity (van Heemst *et al.*, 2005; Suh *et al.*, 2008). However, nothing is known on the molecular adaptations induced by long-term CR in humans, and in particular, on the effects of CR on the regulation of the insulin/IGF-1/FOXO pathway.

Results and discussion

As one of the primary metabolic tissues, skeletal muscle is extremely vulnerable to the effects of aging, and decreases in muscle mass and strength have been associated with increased mortality (Cesari *et al.*, 2009). Interestingly, CR prevents or delays this age-related loss of muscle function and mass, thereby contributing to increases in both the quantity and quality of life (Aspnes *et al.*, 1997; McKiernan *et al.*, 2010). Although research on CR in humans is still at an early stage, information from population and physiological studies suggest that many of the same beneficial metabolic adaptations that occur in experimental animal models are also observed in humans (Fontana & Klein, 2007; Fontana *et al.*, 2010b). We hypothesized that the impressive metabolic changes previously described in these individuals on long-term CR would result in several molecular adaptations, including a down-regulation of the insulin/IGF-1/FOXO pathway, a key nutrient sensing pathway, shown to slow aging in several experimental animals (Kenyon *et al.*, 1993; van Heemst *et al.*, 2005; Kennedy *et al.*, 2007; Piper & Bartke, 2008). We also hypothesized that the relative changes of the skeletal muscle gene expression profiles would be similar between

Correspondence

Luigi Fontana, Division of Geriatrics and Nutritional Science, Washington University School of Medicine, St. Louis, MO, 63108, USA. Tel.: +1 314 747 1485;

fax: +1 314 362 7657; e-mail: lfontana@dom.wustl.edu and

Rafael de Cabo, Laboratory of Experimental Gerontology, National Institute on Aging, National Institutes of Health, Baltimore, MD, 21224, USA. Tel.: +1 410 558 8510; fax: +1 410 558 8302; e-mail: decabora@grc.nia.nih.gov

†These authors contributed equally to this research.

Accepted for publication 12 April 2013



CR rats and humans. In this study, we studied the molecular adaptations induced by long-term CR in healthy lean men and women and compared the skeletal muscle transcriptional profiles induced by CR in rats and humans. Our results show that chronic moderate (~30%) CR in lean and weight-stable adult individuals, despite their genetic heterogeneity, results in a uniform dramatic transcriptional reprogramming of molecular pathways in skeletal muscle, which shifts cellular metabolism from growth to maintenance/repair activities. We also found that CR induces a significant down-regulation of the IGF-1/insulin/FOXO pathway both at the transcriptional and post-transcriptional level. In addition, we found that humans and long-lived CR rats, despite significant genetic, physiological, and anatomical differences, exhibit a number of key common transcriptional adaptations in a major metabolic organ (i.e., skeletal muscle), suggesting that the beneficial gains of CR on healthy longevity would be observed in humans.

We first sought to determine whether CR modifies the gene expression profile in human skeletal muscle. To this end, we recruited and studied 15 middle-aged (58.7 ± 7.4 years), weight-stable very lean ($BMI = 19.2 \pm 1.1 \text{ kg/m}^2$) members of the Calorie Restriction Society who have been practicing ~30% CR with adequate nutrition (at least 100% of RDI for each nutrient) for an average of 9.6 years and a control group of 10 nonobese ($BMI = 25.3 \pm 2.3 \text{ kg/m}^2$) age-matched controls eating a typical Western diet (Table 1). Principle component analysis (PCA) revealed a very distinct separation of groups based on dietary manipulation (Fig. 1A). Remarkably, we found that CR in humans induces dramatic and uniform changes to the gene expression profile within skeletal muscle that are strong enough to overcome the genetic, nutritional, and geographical heterogeneity of this human population. Furthermore, comparison of our study population expression profiles with a younger (31.2 ± 2.0 years) nonobese ($BMI = 25.3 \pm 2.3 \text{ kg/m}^2$) human cohort showed that our CR was grouped closer to the younger profile by PCA (Table 1 and Fig. 1B). To further investigate the role of CR in modifying skeletal muscle gene expression in humans, we next performed parametric analysis of gene set enrichment (PAGE), a computational method that determines differences between genes

and pathways using *a priori* defined gene sets (Kim & Volsky, 2005; Subramanian *et al.*, 2005). PAGE analysis indicated that aging caused a significant down-regulation of pathways associated with muscle contraction, electron transport, and oxidative phosphorylation (Fig. 1D, for a complete list see Table S1). Notably, CR opposes the majority of the transcriptional changes observed in skeletal muscle of middle-aged individuals following a WD. These results indicate that CR in humans can slow down the transcriptional changes associated with aging in skeletal muscle.

As the IGF-1/insulin/FOXO pathway is implicated in improved healthspan, we then sought to determine whether CR modifies this pathway in human skeletal muscle. Importantly, we found that a highly significant number of transcripts along the IGF-1/insulin/FOXO pathway were altered by CR. The PI3K and AKT transcripts were significantly down-regulated 1.7- and 2-folds, respectively (Fig. 2A). Consistently with the gene expression changes, skeletal muscle of humans on long-term CR showed a 35–50% reduction in AKT phosphorylation of the serine and threonine residues (Fig. 2B,C). To our knowledge, this is the first set of data showing that long-term CR in humans down-regulates the activity of the insulin/IGF pathway, which has been shown by Kenyon and others to play a key role in promoting health and longevity in several experimental model organisms (Kenyon *et al.*, 1993; van Heemst *et al.*, 2005; Kennedy *et al.*, 2007; Piper & Bartke, 2008). Importantly, we also found that other transcription factors downstream of AKT, such as FOXO-3A and FOXO-4, were up-regulated (Fig. 2A). It is well known that the inhibition of AKT activates FOXO, which modifies several 'longevity genes' (i.e., stress resistance, antioxidants, DNA repair, protein turnover, and cell death genes) (Lanvin *et al.*, 2007). Consistently, we found that in human skeletal muscle, CR alters several transcripts downstream of FOXO. For example, SOD2, an important antioxidant enzyme, and DDB1, a key DNA repair molecule, were both up-regulated, while cyclin D2, a master regulator of cell cycle progression, was powerfully down-regulated. Several transcripts downstream of FOXO that induce macroautophagy (i.e., beclin-1, autophagin-1, and MAP1LC3B) were also significantly up-regulated (Fig. 2A). FOXO

Table 1 Characteristics of the study subjects

	Humans				Rats		
	WD-Y (<i>n</i> = 5)	WD-M (<i>n</i> = 10)	CR (<i>n</i> = 15)	<i>P</i> value	AL (<i>n</i> = 27)	CR (<i>n</i> = 27)	<i>P</i> -value
Age (years)	31.2 ± 2.0	58.0 ± 7.4	58.7 ± 7.4	0.810	1.3	1.3	–
Sex (M/F)	5/0	8/2	11/4	–	27/0	27/0	–
Body composition							
Height (m)	1.73 ± 8.8	1.76 ± 0.0	1.73 ± 0.0	0.409	–	–	–
Body weight (kg)	78.4 ± 16.3	78.1 ± 9.7	57.5 ± 6.4	<0.0001	0.40 ± 0.7	0.24 ± 0.2	0.001
Body mass index (kg/m ²)	25.0 ± 5.0	25.3 ± 2.3	19.2 ± 1.1	<0.0001	–	–	–
DEXA – NMR							
Fat mass (%)	–	24.0 ± 7.4	13.1 ± 4.8	<0.0001	30.1 ± 0.2	27.2 ± 0.2	0.01
Trunk fat (%)	–	25.6 ± 6.8	11.0 ± 3.5	<0.0001	–	–	–
Lean mass (%)	–	73.1 ± 6.0	81.1 ± 4.8	0.001	60.1 ± 0.2	63.1 ± 0.1	0.03

WD-Y – younger individuals eating Western diets (WD); WD-M – middle-aged individuals on WD; AL – *ad libitum* laboratory diet. For humans, *P*-value comparison CR – WD-M; NMR, nuclear magnetic resonance.

Values are mean ± SD.

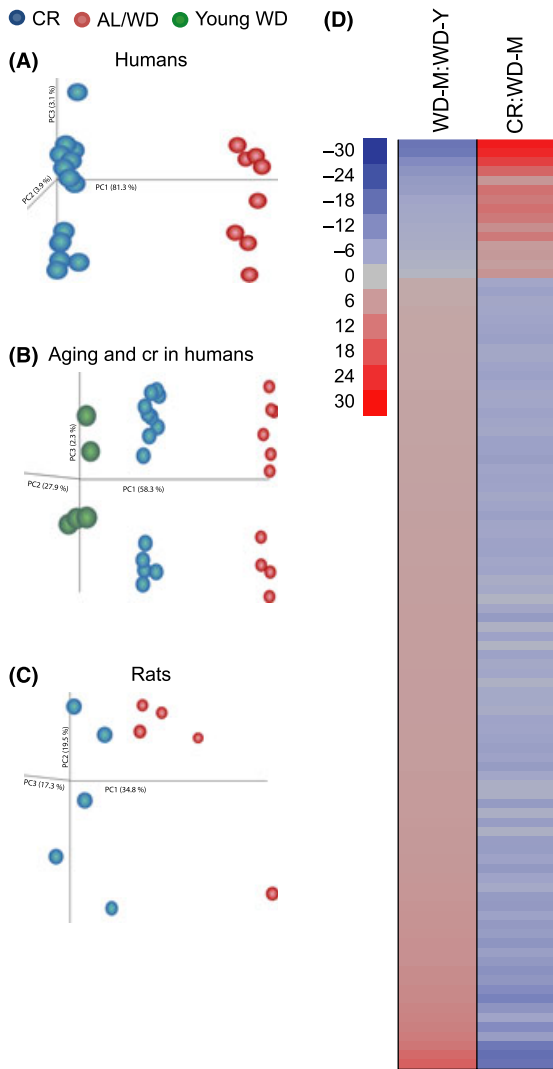


Fig. 1 Principal component analysis (PCA) and parametric analysis of gene set enrichment (PAGE) were performed on microarray data from humans and rats. PCA of (A) humans on caloric restriction (CR) (blue) or *ad libitum* (AL)/Western diet (WD) (red), (B) those of younger subjects on a WD (green), and (C) rats. $n = 5$ for both AL- and CR-fed rats; $n = 10$ and $n = 15$ for humans on WD and CR, respectively; $n = 5$ for younger individuals on WD. (D) PAGE comparing the top 100 significantly pathways up-regulated (red) or down-regulated (blue) by either the WD or CR (WD-Y = younger individuals eating Western diets (WD); WD-M = middle-aged individuals on WD).

is also regulated by two central energy-sensing pathways, SIRT1 and AMPK, which are both activated by decreased nutrient availability (Brunet *et al.*, 2004; Greer *et al.*, 2007). In our study, SIRT2, SIRT4, SIRT5, AMPK β , and AMPK γ transcripts were significantly up-regulated in the human skeletal muscle of the CR participants (Fig. 2A). It is well established that SIRT1 and AMPK control the activity of PGC-1 α , a key transcriptional regulator of mitochondrial metabolism (Wu *et al.*, 1999). Consistently, our findings demonstrate that in human skeletal muscle, CR powerfully increases PGC-1 α gene expression (Fig. 2A), which leads to an up-regulation of several genes that induce mitochondrial biogenesis (Wu *et al.*, 1999), thus opposing the decline in mitochondrial function with age (Anderson & Weindruch, 2007). Transcriptional

profiling also indicates a CR-induced decrease in the inflammatory response, which is implicated in a range of age-related diseases. The beneficial effects of CR may involve an elaborate crosstalk between these highly conserved inflammatory, nutrient- and energy-sensing pathways.

We then wanted to determine whether the overall physiological and molecular response of long-term CR was similar in humans and rats. Rats were subjected to either 40% CR or *ad libitum* (AL) diets early in life. As expected, our rats on a CR-fed diet had increased mean and maximum lifespan compared with those on an *ad libitum*-fed diet (Fig. S1). In humans, nevertheless, such early initiation of CR would be detrimental to growth and development. Therefore, human subjects included in this study were middle-aged men and women. However, it is well known that in rodents, CR initiated at adulthood (12–19 months of age) is as effective as CR begun early in life at decelerating mortality rate, extending remaining lifespan, and inducing dramatic changes in the gene expression profile (Dhahbi *et al.*, 2004). As expected, CR reduced body weight, reduced fat mass, and increased the lean to fat mass ratio in both middle-aged humans and rats compared with those on Western or AL diets, respectively (Table 1). Interestingly, both species exhibited similar responses to CR in several physiological, hormonal, and biochemical markers. Previous studies on these individuals indicate that long-term CR in humans results in improved cardiometabolic profile, markedly lower blood pressure and inflammation, improved left ventricular diastolic function and heart rate variability, and lower serum concentration of insulin, leptin, sex hormones, triiodothyronine, and core body temperature (Fontana & Klein, 2007; Cangemi *et al.*, 2010; Fontana *et al.*, 2010a,b; Soare *et al.*, 2011), all of which are hallmark adaptations also seen in rats in response to CR (Weindruch & Walford, 1988; de Cabo *et al.*, 2003). Interestingly, the effect of CR on circulating IGF-1 concentrations was not significantly reduced in humans unless protein intake is also reduced (Fontana *et al.*, 2008).

Based on the broad phenotypical similarities observed in both species following long-term CR, we next examined whether similarities between humans and rats occurred in gene expression profiles of skeletal muscle as well. PCA revealed a very distinct separation of groups based on dietary manipulation regardless of species (Fig. 1C). PAGE analysis indicated that out of the shared changes, CR evoked a number of common genes and pathways in both species (83 genes and 93 pathways), with the majority of genes being down-regulated by CR (Fig. 3A,B). A subset of gene expression changes were verified by quantitative real-time PCR or QuantiGene-based assays (Table S2). Notably, the 5 most highly elevated transcripts were contractile proteins (Fig. 3C). The list of the 5 most highly down-regulated transcripts include proteins involved in antioxidant responses (NQO1), cholesterol metabolism (NR1H3), fibrosis (PLOD2), and cell growth (IMPDH1). The complete dataset is available at <http://www.ncbi.nlm.nih.gov/geo/>. We identified 93 pathways (22 up-regulated, 71 down-regulated) that were common among rats and humans in response to CR. These included an up-regulation of genes involved in energy metabolism (e.g., TCA cycle, mitochondrial ETC., and glycolysis), as well as a decrease in those in insulin/IGF-1 signaling, and in both the classical and alternative inflammatory pathways

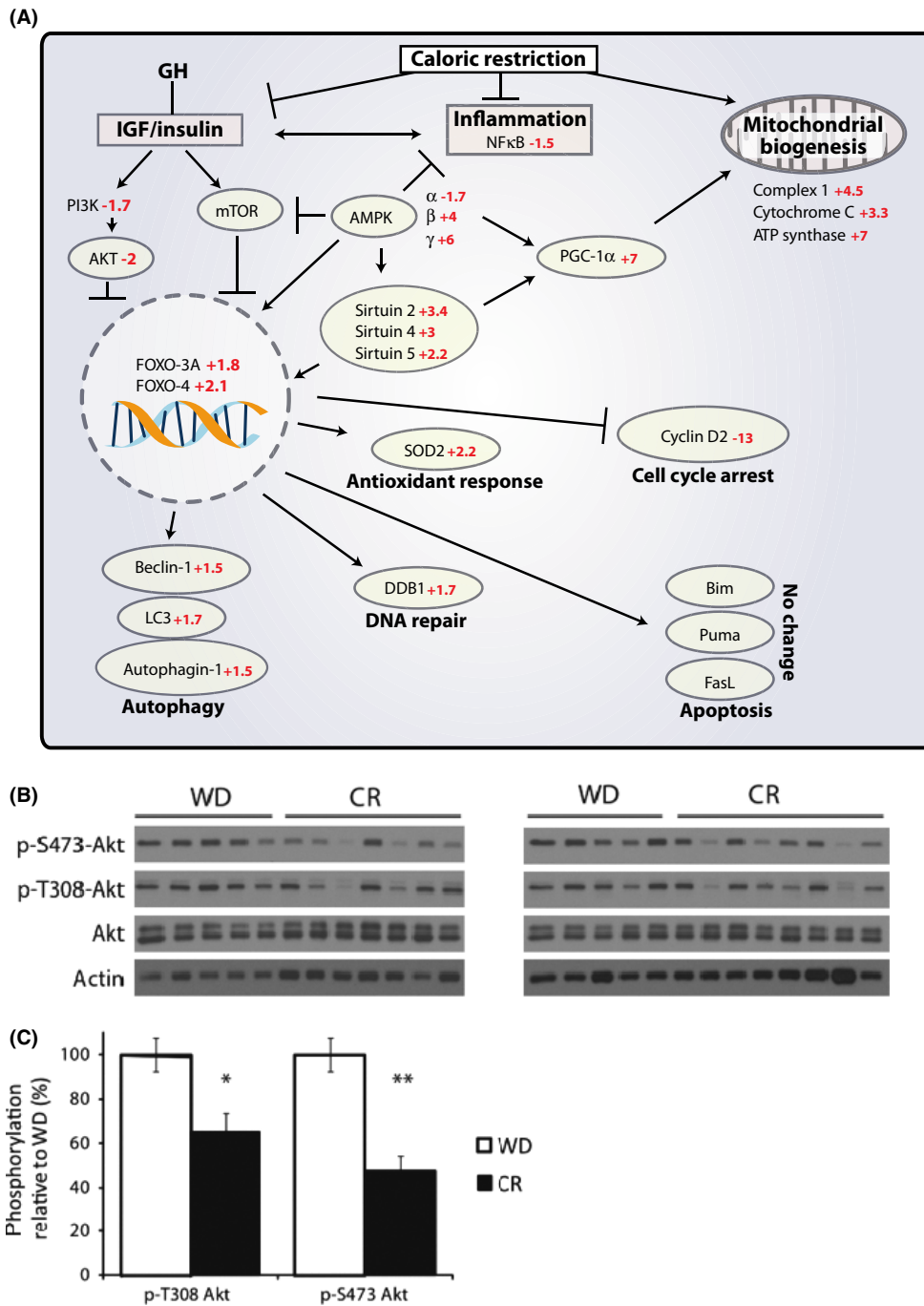


Fig. 2 Transcriptional and post-transcriptional modifications of the PI3K/AKT/FOXO pathway in human skeletal muscle by caloric restriction (CR). (A) Transcriptional down-regulation of the PI3K/AKT/FOXO signaling pathway by CR. GH, growth hormone; IGF, insulin-like growth factor; PI3K, phosphatidylinositol 3-kinase; AKT, protein kinase B (PKB); FOXO-3A, forkhead box O3; FOXO-4, forkhead box O4; mTOR, mammalian target of rapamycin; LC3, microtubule-associated protein 1 light chain 3; AMPK, adenosine monophosphate-activated protein kinase; NFκB, nuclear factor-kappaB; SOD2, superoxide dismutase 2; DDB1, damage-specific DNA binding protein 1; FASL, fas ligand. Western blot of human skeletal muscle from individuals on a Western diet (WD) or caloric restricted (CR) diet. Immunoblot (B) and quantification (C) of Western blots in panel a for p-T308 AKT and p-S473 AKT was performed using NIH ImageJ and normalized to total AKT expression. (* $P < 0.01$, ** $P < 0.00003$ ($n = 10$ WD, 15 CR samples)). Bars indicate mean \pm SEM.

(Fig. 3D,E; for a complete list see Tables S3 and S4). Interestingly, the effects observed on these pathways by CR oppose those normally occurring during the aging process (Park & Prolla, 2005). These results indicate that humans share with other species, such as rats, similar transcriptional responses to CR that are typically associated

with improved health and survival. However, this association does not imply causation for increased longevity. In summary, transcriptional patterns of CR humans suggest that CR may retard the aging process by shifting cellular metabolism from growth to maintenance and repair activities. A molecular trigger for this shift may be the

down-regulation of the IGF/insulin/FOXO signaling pathway, a result that connects our findings to those obtained through genetic manipulation of aging in worms, fruit flies, and rodents (Kenyon *et al.*, 1993; van Heemst *et al.*, 2005; Kennedy *et al.*, 2007; Piper & Bartke, 2008).

Experimental procedures

Study subjects

Rats

Male Fisher 344 rats ($n = 54$) were randomly assigned to two groups at 2 months of age. One group was kept *ad libitum* (AL) fed throughout their lifespan, while the calorie restriction (CR) group was progressively brought down to a 40% CR. All animals were fed a NIH-31 standard chow (Harlan Teklad, Indianapolis, IN, USA). Rats were singly housed in an environmentally controlled vivarium with unlimited access to water and a controlled photoperiod (12 h light; 12 h dark). Body weights and food intake were recorded biweekly. All rats were maintained between 68–72 °F according to animal protocols and NIH guidelines. All animal procedures for this study were reviewed and approved by the Animal Care and Use Committee (ACUC) at the Biomedical Research Center (NIA/NIH).

Humans

Fifteen individuals had been on CR for an average of 9.6 years (4–20 years). Subjects were instructed by an experienced research dietician to record all food and beverages consumed, preparation methods, and approximate portion sizes for seven consecutive days. Food records were analyzed using the NDS-R program (version 4.03_31), which is the Nutrition Data System for research from the Nutrition Coordinating Center at the University of Minnesota. CR subjects consumed a variety of nutrient-dense unprocessed foods

(i.e., vegetables, fruits, nuts, egg whites, fish, poultry, low-fat dairy products, whole grains, and beans) which supplied >100% of the recommended daily intake for all essential nutrients. Refined foods rich in empty calories and trans fatty acids were avoided. Energy intake was 30% lower in the CR group (1773 ± 239 kcal/day) than in the Western diet (WD) group ($n = 10$) (2483 ± 378 kcal/day) ($P \leq 0.0001$). The percentage of total energy intake derived from protein, carbohydrate, fat, and alcohol was 22%, 50%, 28%, and 0.2%, respectively, in the CR group and 17%, 47%, 35%, and 1% in the WD group. The human study was approved by the Human Studies Committee of Washington University School of Medicine, and all participants gave informed consent before their participation. Moreover, a younger cohort of humans ($n = 5$) who underwent surgery for hip dysplasia was included in this study. Written informed consent was obtained from those participants, and the study was approved by the medical ethics committee of the Rizzoli Hospital.

Body composition

Rats

Measurements of lean and fat mass in whole, live rats were acquired by nuclear magnetic resonance (NMR) using the Minispec LF90 (Bruker Optics, Billerica, MA, USA).

Humans

Total body fat mass and fat-free mass were determined by dual-energy X-ray absorptiometry (DXA) (QDR 1000/w, Hologic, Waltham, MA, USA).

Microarray analysis

Five rats per group at 27 months of age were sacrificed and vastus lateralis muscle was flash-frozen. Human percutaneous biopsy

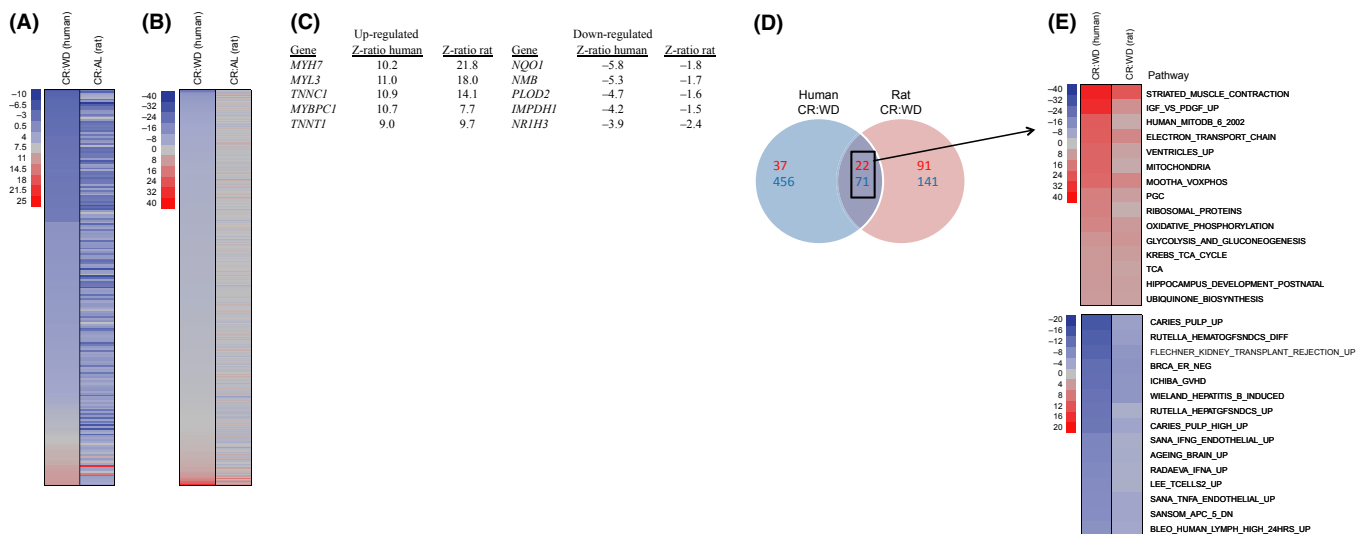


Fig. 3 Parametric analysis of gene set enrichment of microarray data from humans and rats. Columns show every (A) gene or (B) pathway significantly up-regulated (red) or down-regulated (blue) by caloric restriction (CR). (C) The five most highly up-regulated and down-regulated genes, based on Z-ratio in CR compared with WD and AL, respectively. (D) Venn diagram showing the pathway interactions between humans and rats (up-regulated and down-regulated pathways are shown in red and blue, respectively). (E) Cell plot showing the most highly significant up-regulated (red) and down-regulated (blue) common pathways between humans and rats.

specimens of vastus lateralis muscle of middle-aged individuals following CR ($n = 15$) and young ($n = 5$) and middle-aged ($n = 10$) participants eating a standard Western diet (WD) were obtained. RNA was extracted from skeletal muscle samples from both species using Trizol reagent (Invitrogen, Carlsbad, CA, USA) following the manufacturer's instructions and hybridized to RatRef-12 v1 Expression or Human6 Expression v3 and v4 Beadchips (Illumina, San Diego, CA, USA) following protocols listed on the Gene Expression and Genomics Unit of the NIA (<http://www.grc.nia.nih.gov/branches/rfb/dna/index/protocols.htm>). Microarray fluorescent signals were extracted using an Illumina BeadArray 500GX reader. The signals on each sample are normalized by log z-transformation to obtain z-scores and tests for distributions as previously described (Cheadle *et al.*, 2003). Correlation analysis, sample clustering analysis, and principal component analysis including all probes were performed to identify/exclude any possible outliers. The resulting dataset was next analyzed with DIANE 6.0, a spreadsheet-based microarray analysis program. Gene set enrichment analysis used gene expression values or gene expression change values for all of the genes on the microarray. PAGE was used [PubMed 20682848] for gene set analysis. Gene sets include the MSIG database [Link], Gene Ontology Database [Link], GAD human disease, and mouse phenotype gene sets [PubMed: 20092628] were used to explore functional level changes.

RT-qPCR

Rats

Vastus lateralis total RNA from rats was isolated as described above, and first-strand cDNA was synthesized using the High-Capacity cDNA Reverse Transcription Kit (Applied Biosystems, Foster City, CA, USA) according to manufacturer's instructions. Real-time quantitative PCR was performed with SYBR[®] Green PCR master mix on an ABI Prism 7300 sequence detection system (Applied Biosystems). Each sample was analyzed in triplicate, and relative gene expression was normalized to GAPDH. The data were analyzed using the $2^{-\Delta\Delta C_T}$ method. Primer sequences are listed in Table S5 (Supporting information).

Humans

Total RNA was extracted from human muscle biopsies using Trizol as described above. Gene expression levels were quantitated using the Quantigene QuantiGene Plex 2.0 assay according to the manufacturer's protocols (Panomics/Affymetrix, Fremont, CA, USA) (probe set regions are provided in Table S5). To determine the fold change of the genes of interest, we used Partek Genomic Suite to conduct an ANOVA analysis on log₂-transformed background-subtracted Quantigene data, generating a fold change of the CR RNA samples over the WD RNA samples.

Immunoblotting

Vastus lateralis muscles were lysed in 1 mL of cold RIPA buffer (50 mM HEPES pH 7.4, 40 mM NaCl, 2 mM EDTA, 1.5 mM sodium orthovanadate (Na₃VO₄), 50 mM NaF, 10 mM sodium pyrophos-

phate, 10 mM sodium beta glycerophosphate, 0.1% SDS, 1% sodium deoxycholate, 1% Triton) supplemented with phosphatase inhibitor and protease inhibitor cocktail tablets, using a FastPrep 24 (MP Biomedical, Santa Ana, CA, USA) instrument. Protein concentration was determined by Bradford Assay (Bio-Rad, Hercules, CA, USA). 20 µg protein was separated by sodium dodecyl sulfate polyacrylamide gel electrophoresis (SDS-PAGE) on 8%, 10%, or 16% Tris-glycine gels (Invitrogen) and transferred to Immobilon P 0.45 µm PVDF membrane (Millipore, Billerica, MA, USA). Membranes were blocked in 5% milk/TBST, and antibodies were incubated overnight at 4 °C in 5% BSA/TBST (phospho-antibodies) or 5% milk/TBST (all other antibodies). Quantification was performed by densitometry using ImageJ software, and loading was verified by blotting for actin. Antibodies to p-T308 AKT (CST 2965), p-S473 AKT (CST 4060), and total AKT (CST 4691) were from Cell Signaling Technology. The actin (sc-7210) antibody was from Santa Cruz Biotechnology.

Statistical analysis

Subject characteristics were analyzed using Student's *t*-test (two-sample equal variance; two-tailed distribution). Data are expressed as mean ± SD unless indicated otherwise. Survival curves were plotted using the Kaplan–Meier method, which included 27 rats for both CR and AL. Statistical analysis was performed using Sigma-Stat Program for Windows, version 3.5 (Systat Software, Inc., Chicago, IL, USA). A difference with *P*-values < 0.05 were considered statistically significant.

Acknowledgments

Supported by grants from AFAR (American Federation for Aging Research), the National Center for Research Resources (UL1 RR024992), the National Institute of Diabetes And Digestive And Kidney Diseases (P30DK056341). This research was supported in part by the National Institute on Aging-Intramural Research Program, the Longer Life Foundation (an RGA/Washington University Partnership), the Bakewell Foundation, and a donation from the Calorie Restriction Society and the Scott and Annie Appleby Charitable Trust. The funding agencies had no role in the analysis or interpretation of the data or in the decision to submit the report for publication. We thank William Wood and Elin Lehrmann for help with microarray processing and Kevin Becker for microarray data analysis. We also thank the Genome Technology Access Center in the Department of Genetics at Washington University School of Medicine for help with genomic analysis. The Center is partially supported by NCI Cancer Center Support Grant #P30 CA91842 to the Siteman Cancer Center and by ICTS/CTSA Grant# UL1RR024992 from the National Center for Research Resources (NCRR), a component of the National Institutes of Health (NIH), and NIH Roadmap for Medical Research. DWL is a Charles A. King Trust Postdoctoral Fellow; DMS is an Investigator of the Howard Hughes Medical Institute. This publication is solely the responsibility of the authors and does not necessarily represent the official view of NCRR or NIH. Data have been deposited at the Gene Expression Omnibus

(<http://www.ncbi.nlm.nih.gov/geo/>) under accession code GSE38063.

Conflict of interest

The authors declare no conflicts of interest.

Author contributions

E.M.M., S.D.C., R.de C. and L.F. designed the experiments. Protein assays were performed by D.W.L. E.M.M., S.D.C., D.V., D.M.S., R.de C. and L.F. contributed to data analysis and interpretation. Computational methods for analysis of microarray data were developed and applied by L.S., Y.Z., and K.G.B. M.C. and C.F. provided young human muscle biopsies. E.M.M., S.D.C., S.K.-W., R.de C. and L.F. wrote the manuscript.

References

- Anderson RM, Weindruch R (2007) Metabolic reprogramming in dietary restriction. *Interdiscip Top Gerontol* **35**, 18–38.
- Aspnes LE, Lee CM, Weindruch R, Chung SS, Roecker EB, Aiken JM (1997) Caloric restriction reduces fiber loss and mitochondrial abnormalities in aged rat muscle. *Faseb J* **11**, 573–581.
- Brunet A, Sweeney LB, Sturgill JF, Chua KF, Greer PL, Lin Y, Tran H, Ross SE, Mostoslavsky R, Cohen HY, Hu LS, Cheng HL, Jedrychowski MP, Gygi SP, Sinclair DA, Alt FW, Greenberg ME (2004) Stress-dependent regulation of FOXO transcription factors by the SIRT1 deacetylase. *Science (New York, N.Y.)* **303**, 2011–2015.
- de Cabo R, Furer-Galban S, Anson RM, Gilman C, Gorospe M, Lane MA (2003) An in vitro model of caloric restriction. *Exp. Gerontol* **38**, 631–639.
- Cangemi R, Friedmann AJ, Holloszy JO, Fontana L (2010) Long-term effects of calorie restriction on serum sex-hormone concentrations in men. *Aging Cell* **9**, 236–242.
- Cesari M, Pahor M, Lauretani F, Zamboni V, Bandinelli S, Bernabei R, Guralnik JM, Ferrucci L (2009) Skeletal muscle and mortality results from the InCHIANTI Study. *J. Gerontol* **64**, 377–384.
- Cheadle C, Cho-Chung YS, Becker KG, Vawter MP (2003) Application of z-score transformation to Affymetrix data. *Appl. Bioinformatics* **2**, 209–217.
- Dhahbi JM, Kim HJ, Mote PL, Beaver RJ, Spindler SR (2004) Temporal linkage between the phenotypic and genomic responses to caloric restriction. *Proc. Natl Acad. Sci. USA* **101**, 5524–5529.
- Fontana L, Klein S (2007) Aging, adiposity, and calorie restriction. *JAMA* **297**, 986–994.
- Fontana L, Weiss EP, Villareal DT, Klein S, Holloszy JO (2008) Long-term effects of calorie or protein restriction on serum IGF-1 and IGFBP-3 concentration in humans. *Aging Cell* **7**, 681–687.
- Fontana L, Klein S, Holloszy JO (2010a) Effects of long-term calorie restriction and endurance exercise on glucose tolerance, insulin action, and adipokine production. *Age (Dordrecht, Netherlands)* **32**, 97–108.
- Fontana L, Partridge L, Longo VD (2010b) Extending healthy life span – from yeast to humans. *Science (New York, N.Y.)* **328**, 321–326.
- Greer EL, Oskoui PR, Banko MR, Maniar JM, Gygi MP, Gygi SP, Brunet A (2007) The energy sensor AMP-activated protein kinase directly regulates the mammalian FOXO3 transcription factor. *J. Biol. Chem.* **282**, 30107–30119.
- van Heemst D, Beekman M, Mooijaart SP, Heijmans BT, Brandt BW, Zwaan BJ, Slagboom PE, Westendorp RG (2005) Reduced insulin/IGF-1 signalling and human longevity. *Aging Cell* **4**, 79–85.
- Kennedy BK, Steffen KK, Kaeblerlein M (2007) Ruminations on dietary restriction and aging. *Cell. Mol. Life Sci.* **64**, 1323–1328.
- Kenyon C, Chang J, Gensch E, Rudner A, Tabtiang R (1993) A C. elegans mutant that lives twice as long as wild type. *Nature* **366**, 461–464.
- Kim SY, Volsky DJ (2005) PAGE: parametric analysis of gene set enrichment. *BMC Bioinformatics* **6**, 144.
- Larvin O, Bianco S, Kersual N, Chalbos D, Vanacker JM (2007) Potentiation of ICI182,780 (Fulvestrant)-induced estrogen receptor- α degradation by the estrogen receptor-related receptor- α inverse agonist XCT790. *J. Biol. Chem.* **282**, 28328–28334.
- McKiernan SH, Colman RJ, Lopez M, Beasley TM, Aiken JM, Anderson RM, Weindruch R (2010) Caloric restriction delays aging-induced cellular phenotypes in rhesus monkey skeletal muscle. *Exp. Gerontol.* **46**, 23–29.
- Park SK, Prolla TA (2005) Lessons learned from gene expression profile studies of aging and caloric restriction. *Ageing Res. Rev.* **4**, 55–65.
- Piper MD, Bartke A (2008) Diet and aging. *Cell Metab.* **8**, 99–104.
- Soare A, Cangemi R, Omodei D, Holloszy JO, Fontana L (2011) Long-term calorie restriction, but not endurance exercise, lowers core body temperature in humans. *Aging* **3**, 374–379.
- Subramanian A, Tamayo P, Mootha VK, Mukherjee S, Ebert BL, Gillette MA, Paulovich A, Pomeroy SL, Golub TR, Lander ES, Mesirov JP (2005) Gene set enrichment analysis: a knowledge-based approach for interpreting genome-wide expression profiles. *Proc. Natl Acad. Sci. USA* **102**, 15545–15550.
- Suh Y, Atzmon G, Cho MO, Hwang D, Liu B, Leahy DJ, Barzilai N, Cohen P (2008) Functionally significant insulin-like growth factor I receptor mutations in centenarians. *Proc. Natl Acad. Sci. USA* **105**, 3438–3442.
- Weindruch R, Walford RL (1988) *The Retardation of Aging and Disease by Dietary Restriction*. Springfield, IL: Thomas.
- Wu Z, Puigserver P, Andersson U, Zhang C, Adelmant G, Mootha V, Troy A, Cinti S, Lowell B, Scarpulla RC, Spiegelman BM (1999) Mechanisms controlling mitochondrial biogenesis and respiration through the thermogenic coactivator PGC-1. *Cell* **98**, 115–124.

Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web-site.

Fig. S1 Kaplan–Meier survival analyses of *ad libitum* (AL) and 40% caloric restricted (CR) rats.

Table S1 Z-scores of the top 100 pathways significantly changed by either WD or CR.

Table S2 RT-qPCR/QuantiGene based assay validation of micro-array data.

Table S3 Z-scores of common pathways between humans and rats.

Table S4 Z-scores of 3 central pathways altered by CR between humans and rats.

Table S5 Primer sequences and probe set region used for quantitative PCR analysis or Quantigene based assays.