Functional Comparison of Chronological and In Vitro Aging: Differential Role of the Cytoskeleton and Mitochondria in Mesenchymal Stromal Cells

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Abstract

Mesenchymal stromal cells (MSCs) are of high relevance for the regeneration of mesenchymal tissues such as bone and cartilage. The promising role of MSCs in cell-based therapies and tissue engineering appears to be limited due to a decline of their regenerative potential with increasing donor age, their limited availability in human tissues and the need of in vitro expansion prior to treatment. We therefore aimed to determine to which degree in vitro aging and chronological aging may be similar processes or if in vitro culture-related changes at the cellular and molecular level are at least altered as a function of donor age. For that purpose we established MSCs cultures from young (yMSCs) and aged (aMSCs) rats that were cultured for more than 100 passages. These long-term MSCs cultures were non-tumorigenic and exhibited similar surface marker patterns as primary MSCs of passage 2. During in vitro expansion, but not during chronological aging, MSCs progressively lose their progenitor characteristics, e.g., complete loss of osteogenic differentiation potential, diminished adipogenic differentiation, altered cell morphology and increased susceptibility towards senescence. Transcriptome analysis revealed that long-term in vitro MSCs cultivation leads to down-regulation of genes involved in cell differentiation, focal adhesion organization, cytoskeleton turnover and mitochondria function. Accordingly, functional analysis demonstrated altered mitochondrial morphology, decreased antioxidant capacities and elevated ROS levels in long-term cultivated yMSCs as well as aMSCs. Notably, only the MSC migration potential and their antioxidative capacity were altered by in vitro as well as chronological aging. Based on specific differences observed between the impact of chronological and in vitro MSC aging we conclude that both are distinct processes.

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Introduction

Mesenchymal stromal cells (MSCs) are highly proliferative cells that are able to home to and engraft in different tissues and finally differentiate into functional osteoblasts, chondrocytes and/or adipocytes [1]. Their healing-promoting properties result not only from their ability to differentiate into functional mesenchymal cells, but also from their paracrine effects. For instance MSCs serve as source of cytokines and proteinases essential to angiogenesis and matrix-remodeling such as VEGF, MMPs, TGF-β, and bFGF [2,3]. Advantageously, MSCs can be directly obtained from patient’s bone marrow or adipose tissue, thereby avoiding ethical and safety issues associated with the use of embryonic stem cells (ESCs) or induced pluripotent cells (iPSC). Thus, MSCs are thought to be an attractive cell source for cell-based therapies and tissue engineering. In experimental approaches the regenerative capability of MSCs has been validated for femoral head necrosis, osteogenesis imperfecta, large bone defects, infantile hypophosphatasia, GVHD, cartilage defects and tendon repair [4–7].

Even though MSCs therapies have been successful in vitro and in animal settings, a broad clinical application of such therapies is still missing [1]. One reason may be that in mammals the regeneration potential of mesenchymal tissues declines with age, which might be at least partially due to age-related changes in MSC quantity and quality [8,9]. We and other groups demonstrated that chronological aging of the donor is associated with a decline of MSC number, reduced migration potential and diminished differentiation capacity [10,11]. On the molecular level these changes in cellular function were attributed to decreased cytoskeleton turnover, lower antioxidant activity and higher susceptibility towards senescence.

Similarly, also extended MSC expansion in vitro seems to compromise their regenerative function. In this regard, earlier studies already questioned the capability of endless MSC expansion, which may result in loss of progenitor properties and
in malignant transformation [12,13]. This indicates that MSC-based therapeutic strategies require reliable markers for phenotypic, functional and genetic characterization of employed cell populations after in vitro expansion.

Since both individual chronological (in vivo) aging and in vitro aging, due to long-term cultivation, affect MSCs characteristic, the question arises to which degree these two processes differ and in which respect they may be similar. Recently, it has been hypothesized that chronological and in vitro aging of human MSCs induce similar alterations in gene expression [14]. Thus, the aims of this study are to determine a) to which extent in vitro and in vivo aging are related processes leading to similar cellular and molecular alterations, and b) if long-term culture-related changes are altered as a function of the chronological age.

Materials and Methods

Ethics Statement

All experiments involving the use of animals were in compliance with the German Animal Welfare Act (TierSchG §4 [3]) and were approved by State Office of Health and Social Affairs Berlin (Permit Number: IC113-Reg 0232/07).

MSC isolation

MSCs were isolated from the bone marrow of three week and 12 months old male Sprague-Dawley rats (Harlan Winkelmann, Germany, www.harlan.com), selected by plastic adherence and cultured in expansion medium (EM) [10]. Culture medium was substituted twice a week and cells were harvested after reaching 70–80% confluence using trypsin. Cell number and cell diameter distribution of trypsinized MSCs were determined using the cell counter CASY TT (Roche, Germany, www.roche-applied-science.com). The MSC cell surface marker expression was validated using flow cytomtery with specific antibodies (Table S1) as previously described [15].

Functional assays

Proliferation. For short term proliferation assays, 2000 MSCs/cm² were seeded onto 96-well plates (96-MTP). Cell number was measured one and four days after seeding using CyQuant® assay (Promega, Germany, www.promega.com) according to manufacturers instruction.

Migration. Modified Boyden chamber assay was performed as described elsewhere [10]. Briefly, 1×10⁴ MSCs were seeded and incubated for 5 h at 37°C. Non-migrated cells were removed from the upper side; remaining cells stained with 10 μg/ml Hoechst-33342 (Invitrogen, Germany, www.invitrogen.com) and incubated for 5 h at 37°C, and upper layer (0.6% agar) in a 6-well plate. The cells were suspended in the upper layer. The assay was incubated at 37°C and 5% CO₂ for 2–3 weeks. Subsequent, the plates was stained with 0.2% neutral red for 1 h. After washing with PBS, colonies were counted directly using a microscope.

Western blot

The Novex® system was employed according to the Invitrogen NuPAGE® protocol. Primary antibodies were mouse(ző-rat CDKN2A/p16INK4a, mouse(ző-rat CDKN1A/p21WAF1/Cip1) (1:1000, Abcam, Germany, www.abcam.com) and mouse(ző-rat GAPDH) (1:7000, Abcam). As secondary antibody goat(ző-mouse IgG/peroxidase was utilized. Band intensities were quantified by NIH ImageJ software package [http://rsb.info.nih.gov/ij/].

Anchorage-independent growth assay

Soft agar assay was used in order to investigate cell transformation of long-term cultivated MSCs. The assay was performed as previously described [16]. Briefly, the assay consists of a lower layer (1.2% agar) and an upper layer (0.6% agar) in a 6-well plate. The cells were seeded in the upper layer. The assay was incubated at 37°C and 5% CO₂ for 2–3 weeks. Subsequent, the plates was stained with 0.2% neutral red for 1 h. After washing with PBS, colonies were counted directly using a microscope.

Iluminia Bead Chip Hybridization

Total RNA was isolated using Trizol® (Invitrogen) reagent as describes previously [17] and purified using Qiagen RNAeasy® mini kit (Qiagen, Germany, www.qiagen.com) according to manufacturer’s instruction. Illunina® BeadChip hybridization was performed as described elsewhere [18]. Briefly, biotinylated cRNA was produced from 500 ng total RNA using Illunina® TotalPrep™ RNA amplification kit (Invitrogen). Illunina® RatRef-12 Expression BeadsChips hybridization, washing, Cy3 streptavidin staining, and scanning were performed using Illunina® BeadStation 500 platform. Basic expression data analysis was carried out using the BeadStudio software 3.0. Raw data were background-subtracted and normalized using the “rank invariant” algorithm and then filtered for significant expression on the basis of negative control beads. Significant detection of a gene within a sample group was assessed at a detection p≤0.01. Significant regulation of a gene between two groups was assessed at differential p≤0.05 and an expression ratio ≥1.5. Functional categorizing of all differentially expressed mRNAs was performed using the Database for Annotation, Visualization and Integrated Discovery (david.abcc.ncifcrf.gov) [19].

The microarray data is available at Gene Expression Omnibus (http://www.ncbi.nlm.nih.gov/geo/query/acc.cgi?token = nvmlls cciuoocbk&acc = GSE36596) under the accession number GSE36596.

Quantitative real-time polymerase chain reaction (qRT-PCR)

Isolated RNA was reverse transcribed using the iScript™ cDNA Synthesis Kit (BioRad, Germany, www.biorad.com) according to manufacturer’s instructions. The qRT-PCR was performed in the iQ™5 Real-Time PCR Detection System (BioRad) using iQ™SYBR® Green Supermix (BioRad) as described in [17]. All primers employed were intron spanning and their sequences are provided in Table S2. Quantification of mRNA expression of each gene was calculated with the comparative Cycle Threshold (Ct) method normalized with the housekeeping gene.

Immunocytochemistry

Mitochondria network were stained using MitoTracker® Red CM-H₂XRos (MTR) (Invitrogen). Cells were plated into chamber slides one day prior the staining. Cells were incubated with 300 nM MTR for 30 min at 37°C. Subsequently the cells were
fixed using 4% paraformaldehyde and permeabilized with 0.1% saponin dissolved in PBS. Visualization of actin fibers and mitochondria of fixed and permeabilised cells was achieved by incubation with Alexa 594-conjugated phalloidin (6.0 nM; Invitrogen) or with specific mouse (2- rat Cytochrome C) antibody (BD Biosciences, Germany, www.bdbiosciences.com). Nuclei were stained with DAPI and goat (2-mouse IgG)-488 (Invitrogen) was used as secondary antibody. Fluorescence imaging was performed with a Leica DMi6000B live cell microscope system (Leica, Germany, www.leica.com) under identical excitation and exposure conditions. Cell area and cell roundness as well as mitochondria network area were quantified using Columbus 2.0 software (PerkinElmer, Germany, www.perkinelmer.de) and results are presented as mean ± standard deviation (SD). All tests were analyzed two-sided and p<0.05 was regarded as significant.

**Results**

**Generation of in vitro aged MSCs**

In order to establish in vitro aged MSC cultures from young (3 weeks) and aged (12 months) SD-rats, isolated MSCs were sub-cultured under standard cell culture conditions until passage 100 (P100). Unexpectedly, long-term culture of MSCs from aged (aMSCs) and young (yMSCs) rats did not diminish their proliferation rate as indicated by the number of population doublings (PD) per passage (Figure 1A). Both, aMSCs and yMSCs exhibited a similar proliferation rate throughout the long-term culture (±SD: PDaMSC = 2.7 ± 0.8; PDyMSC = 2.4 ± 0.3; p = 0.450). All MSC cultures were maintained for more than 100 passages without ultimately reaching the state of cell cycle arrest.

To further characterize the background of the in vitro aging process, a pair of long-term cultivated aMSCs and yMSCs of P100 (aMSCSP100; yMSCSP100) and P30 (aMSCSP30; yMSCSP30) were functionally and biochemically investigated and compared to primary MSCs of P2 (aMSCSP2; yMSCSP2). No differences in proliferation between primary and in vitro aged aMSCs and yMSCs of P2, P30, and P100 were determined (Figure 1B).

However, Western Blot analysis revealed a significant increased expression of the cell cycle inhibitors p21 and p16 in long-term cultivated aMSCs and yMSCs of P30 and P100 compared to aMSCs and yMSCs of P2 (Figure 1C and D).

The tumorigenic potential of in vitro aged MSCs was estimated by an anchorage-independent growth assay. In contrast to the breast carcinoma cell line MDA-MB-231, which served as positive control, in vitro aged MSCSP100 showed no growth in soft agar (Figure 1E) indicating a non-transformed status.

Next, we analyzed alterations in morphology of MSCs upon in vitro aging. During the course of long-term cultivation the cell diameter of aMSCs and yMSCs decreases (aMSCs: meanP90 = 16.3 ± 3 μm, meanP100 = 16.2 ± 3 μm, pP90 vs. P100 = 0.001; yMSCs: meanP90 = 20.5 ± 5 μm, meanP100 = 17.5 ± 3 μm, pP90 vs. P100 < 0.001; Figure 2A). Morphological analysis of fixed and phalloidin stained MSCs demonstrated a significantly larger cell area of aMSCSP2 (meanP2 = 4182 ± 100 μm²) and yMSCSP2 (meanP2 = 4291 ± 97 μm²) compared to their in vitro aged counterparts (aMSCSP2: meanP2 = 3397 ± 144 μm², p = 0.019; yMSCSP2: meanP2 = 2045 ± 92 μm², p = 0.001; Figure 2B). The observed morphological changes were not only restricted to the cell size. Compared to the primary MSCSP2, in vitro aged aMSCs and yMSCs exhibited also less filopodia and lamellipodia, diminished cell spreading and increased cellular roundness (Figure 2C, Figure S1).

**Long-term cultivation adversely affects differentiation and migration potential of MSCs**

In order to analyze the influence of in vitro aging on the MSCs phenotype, their cell surface marker patterns were determined by
flow cytometry. In line with recent findings MSC cell surface markers CD29, CD44, CD73, CD90, CD105, CD106, CD166, and RT1A were expressed on in vitro aged aMSCs P100 and yMSCsP100 (Figure S2). Moreover, in vitro aged aMSCs P100 and yMSCsP100 were negative for CD45, CD34 and RT1B.

The MSC differentiation potential was tested by stimulation with osteogenic (OM) and adipogenic media (AM). Cells cultured in expansion medium (EM) served as negative control. In contrast to MSCsP2, in vitro aged aMSCsP30 and yMSCsP30 showed no matrix mineralization (ODAB/ODAR relative to negative control: mean aMSCsP2 = 8.6±1.5; mean aMSCsP30 = 1.1±0.4; pP2 vs. P30 <0.001; mean yMSCsP2 = 1.2±0.4; pP2 vs. P30 <0.001; mean yMSCsP30 = 9.3±2.1; mean yMSCsP100 = 1.5±0.5; pP2 vs. P30 <0.001; mean yMSCsP100 = 0.82±0.21; pP2 vs. P100 <0.001) (Figure 3A). This loss in osteogenic differentiation capacity appeared to be independent from donor age as both in vitro aged cultures showed no matrix mineralization. In a complementary approach MSCs were differentiated into the osteogenic direction by OM supplementation with BMP2. Similarly to dexamethasone stimulation, BMP2 induced strong matrix mineralization in aMSCsP2 and yMSCsP2 but not in long-term cultured MSCsP30 and MSCsP100 (Figure 3B).

The adipogenic differentiation potential of the in vitro aged aMSCsP2 (meanOR/AB = 0.28), yMSCsP2 (meanOR/AB = 0.34), aMSCsP100 (meanOR/AB = 0.30) and yMSCsP100 (meanOR/AB = 0.29) was significantly decreased compared to aMSCsP2 (meanOR/AB = 0.53, pP2 vs. P30 = 0.011, pP2 vs. P100 = 0.003) and yMSCsP2 (meanOR/AB = 0.49, pP2 vs. P30 = 0.039, pP2 vs. P100 = 0.018), but remained significantly higher than the negative control cultured in EM (meanOR/AB = 0.17) (Figure 3C). Likewise to osteogenic differentiation, no difference in adipogenic differentiation properties

Figure 1. Generation and characterization of in vitro aged MSCs. (A): Cumulative population doublings of aMSCs and yMSCs during the first 80 days of culture are shown (n = 5). (B): Long-term cultivation has no influence on short-term proliferation rate of aMSCs and yMSCs of passage 30 and 100. Proliferation assay was performed using CyQuant®. (C): Graphs illustrate quantified signal intensities of p21WAF/CIP1 and p16INK4A relative to GAPDH. (D): Representative Western blots showing increased p21WAF/CIP1 and p16INK4A expression during in vitro aging. GAPDH served as endogenous control. (E): In anchorage-independent growth assays in vitro aged MSCsP100 did not form colonies, while the breast carcinoma cell line MDA-MB-231, which served as positive control, produced numerous colonies (n = 3). Abbreviations: aMSCs, mesenchymal stromal cells from aged donors; yMSCs, mesenchymal stromal cells from young donors; P: passage. * indicates statistical significance (p<0.05).

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was observed between aMSCs and yMSCs at the same passage number.

Since it is known that primary aMSCs and yMSCs differ in their migration capacity [10], the migration potential of MSCs after long-term cultivation was assessed. With a modified Boyden chamber assay a significantly decreased migration rate of in vitro aged MSCs P30 and MSCs P100 compared to their primary counterparts was measured (Figure 3D). Moreover, the MSC migration potential declined significantly with the donor age (aMSCs vs. yMSCs; pP2 = 0.029, pP30 = 0.010, and pP100 = 0.031). Thus, our findings indicate an impact of both chronological and in vitro aging on MSC migratory capacity.

Expression of genes associated with actin cytoskeleton organization and mitochondrial capacity is altered during in vitro MSC aging

To supplement our functional analysis we compared the transcriptome of aMSCs and yMSCs at different in vitro passages...
with primary MSC_P2 cultures. Using Illumina® BeadArray technology, approximately 9000 genes were significantly detected in MSC_P2 and yMSC_P2, while approximately 8000 genes were detected in each group of in vitro aged cells (Figure 4A). This observation indicates alterations of the expression profiles during increased cultivation time, which is supported by diminished correlation coefficients (r^2) for MSC_P30 and MSC_P100 compared to MSC_P2 cultures. Functional annotation clustering revealed 431 genes specifically expressed in MSC_P2, 124 genes specifically expressed in long-term MSC_P30 and MSC_P100, and 7103 genes that are expressed in either of them (Figure 4B). Pathway analysis detected in MSC_P2 chemokine signaling, negative regulation of apoptosis, cell migration, and calcium ion homeostasis as specific functional clusters (Table S3). In long-term MSC_P30 and MSC_P100 exclusively expressed genes clustered to Notch signaling, cell cycle progression and category of receptors (Table S4).

Figure 3. Long-term cultivation negatively influences the differentiation and migration potential of aMSCs and yMSCs. (A): In contrast to primary MSCs of passage 2, in vitro aged aMSCs and yMSCs of P30 and P100 show no matrix mineralization. Osteogenic differentiation was initiated with dexamethasone and determined by matrix mineralization (Alizarin Red, AR) and normalized to cell number (alamarBlue®, AB). Dashed lines indicate differentiation potential of the negative control cultured in EM. (B): Under stimulation with BMP2, aMSCs and yMSCs of P2 show strong osteogenic differentiation, while again no matrix mineralization was observed in long-term MSC cultures of P30 and P100. (C): Adipogenic differentiation of aMSCs and yMSCs of P30 and P100, induced by adipogenic medium, was diminished by 50% compared to aMSCs and yMSCs of P2. In reference to the negative control maintained in EM (dashed line), aMSCs and yMSCs of P30 and P100 retained a potential for adipogenic differentiation. Differentiation was determined by using Oil red O (OR) staining and normalized to cell number. Diagram shows values normalized to negative control. (D): The number of migrated cells declined with increased in vitro passage. Moreover, aMSCs of each passage demonstrated significantly lower migratory potential compared to yMSCs. Migration rates were measured with a modified Boyden chamber assay. At least five independent experiments were carried out for all assays. Abbreviations: OD, optical density. * indicates statistical significance (p<0.05). doi:10.1371/journal.pone.0052700.g003
To further explore pathways that are specific for primary but not in vitro aged MSCs, we performed a detailed analysis of down- and up-regulated genes (detection p<0.01, expression ratio >1.5, differential p<0.05). In total 1199 mRNAs were differentially expressed between MSCsP30 and MSCsP2 (MSCsP30/MSCsP2: nup-regulated = 460; ndown-regulated = 739). The expression of 1542 mRNAs was altered between MSCsP100 and MSCsP2 (MSCsP100/MSCsP2: nup-regulated = 660; ndown-regulated = 674).

Functional annotation clustering of up-regulated genes upon long-term cultivation (Table S5) revealed an association of cell cycle progression, DNA replication, p53 signaling, and mitogen-activated protein kinase (MAPK) signaling with MSC in vitro aging (Figure 4C and D). Overall, these up-regulated pathways were more prominent in aMSCsP100 than in yMSCsP100. Genes involved in the insulin signaling pathway, were also up-regulated in long-term cultivated aMSCs, while only a minority of these genes were up-regulated in long-term cultivated yMSCs.

Table 4. Transcriptional profiling of aMSCs and yMSCs at P2, P30 and P100. (A): The absolute number of genes detected after thresholding diminished during advanced in vitro culture independent from donor age (second column). The correlation coefficient (r²) was significantly reduced between aMSCs and yMSCs of P30 and P100 compared to P2. Only minor differences in gene expression were detected between aMSCs and yMSCs of each passage. (B): Functional annotation clustering of genes exclusively expressed either in primary MSC of P2 or in vitro aged MSCs of P30 and P100 revealed 431 and 124 differentially regulated genes, respectively. At P2 genes were mainly associated with chemokine signaling, apoptosis, cell migration, and calcium homeostasis. Whereas at P30 and P100 exclusively expressed genes are involved in Notch signaling, cell cycle progression and receptor signaling. (C): Analysis of pathways down-regulated after long-term in vitro culture revealed involvement of mitochondria, focal adhesions, cytoskeleton organization, TGF-β/BMP, WNT, and PPARγ signaling. Pathways up-regulated upon long-term in vitro culture were associated with cell cycle progression, DNA replication, p53, MAPK, and insulin signaling. (D): Differential statistical analysis summarizes all pathways and genes significantly up- and down-regulated during in vitro culture. The most numerous genes down-regulated during in vitro aging of aMSCs and yMSCs were associated with focal adhesions, actin cytoskeleton organization and mitochondrial function.

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Annotation clustering of down-regulated genes upon in vitro aging (Table S6) revealed an association with focal adhesion function, actin cytoskeleton organization, TGF-β, WNT, PPARγ signaling, and mitochondrial capacity (Figure 4C and D). The down-regulation of genes with focal adhesion and actin cytoskeleton function is well consistent with our functional observations showing a reduced cell size, diminished cell spreading and decreased migration capacity of in vitro aged MSCsP100 and MSCsP30. Alterations in gene expression associated with the Tgf/Bnp signaling pathway, which is supported by impaired osteogenic differentiation of in vitro aged MSCs under Bmp2 stimulation, was validated by quantitative real time RT-PCR. In accordance with transcriptome analysis, the expression of Bmpr1a, Bmpr2 and Bmp6 was down-regulated in MSCsP100 compared to primary MSCsP2 (Figure S3). In addition, aMSCsP2 displayed a significant higher expression level of Bmp6 compared to yMSCsP2. Moreover, Bmp2 expression was elevated in aMSCsP100, whereas it was reduced in yMSCsP100 compared to primary aMSCsP2 and yMSCsP2. Similarly, the expression of Bmpr1b was down-regulated in aMSCsP100, while it was up-regulated in yMSCsP100 compared to primary MSCsP2. Transcriptome analysis surprisingly demonstrated a specific impact of long-term in vitro culture on mitochondrial capacity, oxidative phosphorylation and glutathione metabolism of MSCs. This suggests a critical impact of energy metabolism for primary MSC function.

The course of long-term cultivation alters mitochondria function

According to our ontology analysis, a major group of genes down-regulated upon in vitro aging is related to mitochondria. To further validate these in silico data functionally, the mitochondria network morphology was assessed (Figure 5A). During in vitro culture the ratio of mitochondria network area to the total cell area increases (Figure 5B).

We further measured the antioxidant power in lysates of in vitro aged MSCs using the Trolox® equivalent antioxidant capacity (TEAC) assay. With increased passage number a general reduction in antioxidant capacity was detected (aMSCs: TEACp2 = 76 μM, TEACp30 = 68 μM p = 1.000, TEACp100 = 41 μM p = 0.001; yMSCs: TEACp2 = 102 μM, TEACp30 = 81 μM p = 0.035, TEACp100 = 63 μM p < 0.001) (Figure 5C). Moreover, the total antioxidant capacity in yMSCs was generally higher than in aMSCs at all different passages.

The mitochondrial function was further assessed by measuring the ATP content, production of intracellular ROS and the mitochondrial membrane potential (ΔΨm). Long-term cultivated MSCsP30 and MSCsP100 exhibited a significantly reduced content of cellular ATP than the primary MSCsP2 (aMSCs: ratioP2 = 19.1 nM/ngDNA, ratioP30 = 12.8 nM/ngDNA p = 0.040, ratioP100 = 12.3 nM/ngDNA p = 0.025; yMSCs: ratioP2 = 25.9 nM/ngDNA, ratioP30 = 13.0 nM/ngDNA p = 0.001, ratioP100 = 13.1 nM/ngDNA p = 0.001) (Figure 5D). Notably, no donor age-dependent difference in the ATP content was observed in the long-term cultivated as well as primary MSC populations.

Conversely to the decreased ATP content, intracellular ROS levels were found to be increased during in vitro aging (Figure 5E). Long term cultivated MSCs exhibited significant higher level of intracellular ROS compared to their primary counterparts (aMSCs: ratioP2 = 34.7FI/ngDNA, ratioP30 = 71.3FI/ngDNA p = 0.002, ratioP100 = 72.6FI/ngDNA p = 0.021; yMSCs: ratioP2 = 34.5FI/ngDNA, ratioP30 = 69.2FI/ngDNA p = 0.006, ratioP100 = 72.8FI/ngDNA p = 0.020). Under pyocyanin treatment, which induces intracellular ROS, all tested MSC population showed a significant increase of intracellular ROS level.

The proliferation capacity of the most cell types is limited. After a certain number of cell divisions, the population expansion is slowed down, before the cells ultimately stop dividing [25]. Moreover, it is assumed that the number of cell division cycles decreases with the donor age. In our study, we observed no ultimate cell cycle arrest of the entire cell population during in vitro aging of aMSCs and yMSCs from rats. Culture of aMSCs and yMSCs occurred for more than 100 passages at relative constant proliferation rates, suggesting extension of lifespan and possibly spontaneous immortalization. Extended long-term culture might result in spontaneous immortalization of murine as well as human MSCs [13,26,27]. In contrast to other studies, neither aMSCsP100 nor yMSCsP100 showed growth in a soft agar assay suggesting an untransformed status [28]. Notably, a non-transformed status does not exclude the occurrence of aneuploidy in long-term cultivated MSCs. Other groups have shown that MSCs with chromosomal instabilities exhibited no evidence of transformation either in vitro or in vivo and enter senescence [29]. Accordingly, transcriptional analysis revealed an up-regulation of genes associated with the tumor suppressor p53 signaling pathway. This pathway promotes replicative and premature senescence as well as apoptosis [30,31]. It seems to be progressively activated during aging in response to various cellular stresses, including DNA damage and oncogene activation [32]. Correspondingly, p53 signaling is inactive in the majority of human cancer cells and partially accounts for their resistance to senescence [30]. Thus, in vitro aging induces increased p21WAF1/CIP1 and p16INK4A expression pointing to a higher proportion of senescent cells in long-term cultivated MSCs.

It is important to note that increased expression of senescence markers in long-term cultivated MSC population does not necessarily indicate a decline in replicative potential of each individual cell. Rather to replicative senescence, a proportion of individual cells might undergo stress-induced premature senescence in response to intracellular stress like oxidative stress,
Figure 5. Long-term cultivation of MSCs alters their mitochondrial function. (A): Fluorescence microscopy was used to investigate the morphology of the mitochondrial network within long-term cultivated and primary aMSCs and yMSCs. Upon in vitro aging mitochondrial network appeared to be altered. Images show immunofluorescence of mitochondria and the actin cytoskeleton stained with a specific antibody recognizing cytochrome C and Alexa 594-conjugated phalloidin, respectively. Nuclei were counterstained with DAPI. (B): During in vitro aging the relative mitochondrial area per cell area increases in aMSCs and yMSCs of passage P30 and P100 compared to P2. The mitochondrial network and the cellular area were quantified after staining with MitoTracker™ Red and phalloidin, respectively. Diagram values represent ratio of the mitochondria network area relative to the cell area. (C): The total antioxidant capacity decreases with increasing passage number. Moreover, yMSCs of P2 and P100 exhibited significant higher antioxidant activities than aMSCs of the same passage. The Trolox™ equivalent antioxidant assay kit was used to determine the total antioxidant capacity of whole MSC lysates and quantified against a Trolox™ standard row. (D): Intracellular ATP levels decline significantly in long-term cultivated aMSCs and yMSCs of passage P30 and P100. Cellular ATP was determined using ATPLite™ bioluminescence luciferase-based assay and normalized to total DNA content determined by CyQuant™. (E): Long-term cultivated yMSCs and aMSCs of P30 and P100 displayed higher ROS...
production than primary MSCs of P2. After treatment with pyocyanin, which increases ROS levels, the observed difference between P2 and P30/P100 remained but the absolute value amplified about 2-fold. Intracellular ROS level were determined using CM-H2-DCFDA and normalized to total DNA content. Measurement of the mitochondrial membrane potential (∆Ψm) revealed a progressive increase during in vitro aging with highest values in aMSCs of P100. Upon treatment with valomycin, an inhibitor of the mitochondrial respiratory chain, ∆Ψm declined in aMSCs and yMSCs of all passages. The mitochondrial ∆Ψm was determined with the MitoProbe® JC-1. * indicates statistical significance (p<0.05).

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irreversible DNA damage or genomic instability [30,33]. For example, it was shown that both chemical and culture-induced oxidative stress cause DNA damages and aneuploidy in human MSCs, which subsequently undergo senescence [34].

The loss of cells due to senescence might be counterbalanced by other fast growing cells, marked by the up-regulation of genes associated the cell cycle progression, which explains the unaltered proliferation rate of the whole in vitro aged MSC populations in comparison to the primary MSC cultures.

In vitro aging negatively affects the differentiation capacity of aMSCs and yMSCs

Long-term culture not only affects aMSCs and yMSCs on a molecular level; it also alters their morphology and has functional consequences. MSCs of P30 and P100 were no longer able to differentiate into the osteogenic lineage and the ability to differentiate into the adipogenic lineage was markedly decreased. These results are consistent with several other studies showing a reduced differentiation potential in human and murine MSCs upon in vitro aging [35-38]. The mRNA expression analysis revealed a decreased expression of genes involved in Wnt and Tgf-β/Bmp signaling upon long term culture. The Wnt pathway is clearly required throughout osteogenesis and substantial elevated Wnt/β-catenin signaling triggers the differentiation of MSCs into the osteogenic lineage [39-42].

A pivotal role of Bmp signaling is the induction of bone and cartilage formation [43]. BMPs induce the differentiation of mesenchymal cells and also enhance the function of osteoblasts (matrix synthesis) [44]. Some studies have pointed out that BMP signaling is also required for adipogenic differentiation of mesenchymal precursor cells [44]. Accordingly, we observed decreased adipogenic differentiation potentials of long-term cultivated MSCs and a down-regulation of genes involved in the PPARγ pathway. The PPARγ pathway positively regulates the adipocytic differentiation of MSCs and intracellular accumulation of lipids by modulating genes involved in their uptake and metabolism [45].

Notably, the BMP- as well as dexamethasone induced osteogenic differentiation was impaired in long-term cultivated MSCs. Also others have reported that a decreased differentiation potential upon dexamethasone-induced osteogenic differentiation is associated with altered Bmp-receptor mRNA expression [44-46]. This observation emphasizes the important role of down-regulated BMP signaling for the diminished differentiation potential of in vitro aged MSCs. Results from several studies have led to the assumption that the BMP pathway cooperates with other pathways, especially the canonical Wnt-signaling [46-48], to drive osteogenic differentiation. For example, the knock-out of the Wnt/β-catenin antagonist Axin2 leads to enhanced nuclear accumulation of β-catenin and increased levels of BMP2, BMP6 and phospho-Smad, which further promotes osteogenic differentiation of osteoprogenitor cells and enhances bone formation in vitro and in vivo, respectively [49,50]. In both studies, the effect of the Axin2 knockout on BMP-signaling and osteogenic differentiation could be reversed by β-catenin inactivation. Collectively, there is growing evidence suggesting that osteogenic differentiation of osteoprogenitor cells is highly dependent on the cross talk between Wnt and BMP signaling [46]. Moreover, aMSCs and yMSCs exhibit exclusive expression of several genes belonging to the Notch signaling pathway upon in vitro aging. The Notch signaling pathway is known to suppress osteogenic differentiation and markedly decreases trabecular bone mass in adolescent mice [51]. Thus, the observed alterations in Tgf/Bmp-, Wnt-, Pparaγ-, Mapk- and Notch signaling pathway might act together and lead to the loss of differentiation ability after long-term culture. Altogether, transcriptomes of in vitro aged aMSCs and yMSCs are clearly distinct from primary MSCs (approx. 85% correlation); therefore a complete loss of progenitor characteristic with long-term cultivation is reasonable to expect. In conclusion, long-term survival of MSCs in culture is achieved at the cost of differentiation potential. Furthermore, in vitro cell culture conditions favor expansion of cells with high proliferation potential rather than those with high differentiation potential. Here we have shown that in vitro aged MSCs express common markers of the MSCs phenotype, which highlights the lack of reliable markers for multipotent MSCs.

Altered morphology and migration potential upon in vitro aging

Apart from the negative influence of in vitro aging on MSC differentiation potential, extended long-term culture might also lead to other functional alterations. For instance, recently we and others have shown that chronological aging has a significant impact on cell migration, cytoskeleton organization and actin turnover [10,52]. As MSCs for each therapeutic approach crucially rely on proper migration towards stimuli for functional engraftment, we analyzed aMSCs and yMSCs for this aspect in more detail. Random (undirected) migration potential of MSCs in our study was affected by both in vitro aging status and age of donor animals. Cellular migration, which requires coordinated contact to the extracellular substrate followed by detachment, strongly depends on local cytoskeleton organization and actin turn-over [53]. The impact of local actin organization for migration is accentuated by the importance of lamellipodia, filopodia and focal complex formation for cellular migration [54]. In line with the reduced MSC migration potential upon in vitro and chronological aging, diminished expression of genes associated with focal adhesion and actin cytoskeleton organization was observed. Differential gene regulation was more prominent between primary and long-term cultivated cells than between aMSCs and yMSCs of the same passage as reflected by a higher number of affected genes, higher degree of differential expression as well as lower p-values. By immunofluorescence analysis, we demonstrated that during long-term cultivation size of aMSCs and yMSCs as well as their filopodia and lamellipodia number decreases, while their cell roundness increases. Correspondingly, with increasing passage number we observed a donor-age independent decline in mRNA expression of specific genes subsets encoding cytoskeletal and focal adhesion proteins such as integrins, alpha-actinins, actin related protein 2/3 complex, Rho-associated coiled-coil forming kinases (ROCK), collin, and profilin.

Although undirected transmigration rather than chemotaxis was investigated, it needs to be highlighted that we further observed a down-regulation of mRNAs of several chemokines, cytokines and their receptors during chronological and in vitro aging, e.g. stromal
cell-derived factor 1 (Sdf-1) and its receptor (Cxcr4). On molecular level, it is assumed that specific chemokines and their receptors play a critical role to direct MSCs to their desired site of action. Studies investigating skeletal repair and systemic skeletal disorders in animal models showed that Cxcr4 and SDF-1 recruit MSCs to the fracture site and prevent bone loss [53].

Oxidative stress might cause the decline of MSC functionality upon in vitro aging

Transcriptome analysis revealed a passage-dependent decline in the expression of mRNA associated with mitochondria, oxidative phosphorylation, glutathione metabolism, and antioxidant defense. These expression changes were accompanied by altered mitochondrial morphology, reduced antioxidant capacity, increased ROS levels, enhanced ΔΨm, and diminished intracellular ATP concentrations. Dysfunctional mitochondria, which are a natural source of free radicals and ROS, lead to increased intracellular ROS concentration, impaired ATP production and causes stress-induced senescence in normal somatic cells as well as in MSCs [56–58]. This together suggests that the higher expression of senescence markers in long-term cultured MSCs may be caused by increased intracellular stress. In human ESCs and iPSCs alterations in mitochondrial number and activity suppress the mitochondrial/oxidative stress pathway. Moreover, iPSCs exhibit alterations of senescence-related p53 signaling pathway compared to their differentiated and subsequently transformed cellular origin. Furthermore, long-term cultured hESCs are characterized by dysfunctional mitochondria potentially compromising their long-term pluripotency [59].

Similar to our observations, the same study associated an elevated mitochondria network volume with increased ΔΨm and ROS levels. These changes were attributed to a diminished removal of damaged mitochondria and/or fusion of existing mitochondria in order to compensate for mitochondrial dysfunction. Although chronological aging also affects MSCs antioxidant capacity and glutathione metabolism, we find no difference in the basal ROS levels comparing aMSCs and yMSCs. This observation is in line with other studies demonstrating unaffected ROS production in cells from aged and young adult rats [60]. Thus, our findings suggest that increased intracellular oxidative stress might be the basis for the progressive functional decline of aMSCs and yMSCs during long-term in vitro culture. Mitochondrial dysfunction marked by increased ROS concentrations may lead to DNA and protein damage, which in turn might activate p53 signaling increasing the amount of senescent and dysfunctional cells. These detrimental effects seem to occur independently of the donor age during in vitro expansion and support the idea that chronological and in vitro aging are distinct processes.

Conclusion

Long-term in vitro culture, but not chronological aging, compromises the osteogenic and adipogenic differentiation capacity of MSCs and alters their morphology, susceptibility to senescence and mitochondrial function. Accordingly, transcriptome analysis revealed that chronological and in vitro aging results to a large extent in divergent changes at the molecular level. Thus, independent from donor animal age, in vitro aging of MSCs seems to result in complete loss of their progenitor characteristics. Although, in vitro aging alters the migration potential and antioxidative capacity of MSCs as a function of the donor age, results of this study collectively suggest that both are distinct processes. Even if our present study is in some way limited by the usage of rat MSCs instead of human MSCs, it provides direct comparison between in vitro and chronological aged MSC not only at the cellular but also at the molecular level. Perspectives, therapeutic approaches utilizing MSCs should critically review in vitro expansion.

Supporting Information

Figure S1 Cell roundness increases during long term culture of aMSCs and yMSCs. Actin fibers were stained with Alexa 594-conjugated phalloidin (6.6 nM). Nuclei were counterstained with DAPI. Fluorescence images were taken under identical excitation and exposure conditions. Cell roundness was quantified using Columbus 2.0 software (PerkinElmer) and results are presented as mean ± standard error of the mean (SEM). Abbreviations: aMSCs, mesenchymal stromal cells from aged donors; yMSCs, mesenchymal stromal cells from young donors; P, passage; * indicates statistical significance (p<0.05).

Figure S2 Cell surface marker pattern of long-term cultivated aMSCs and yMSCs of passage 100. MSC phenotype was characterized by flow cytometry (n = 3). Representative pictures are shown: Both aMSCs and yMSCs of passage 100 were positive for CD29, CD44, CD73, CD90, CD105, CD106, CD166 and RT1A as well as negative for CD45, CD34 and RT1B. Abbreviations: aMSCs, mesenchymal stromal cells from aged donors; yMSCs, mesenchymal stromal cells from young donors; P, passage; * indicates statistical significance (p<0.05).

Figure 3 Down-regulation of Bmpr1a, Bmpr1b and Bmpr2 as well as Bmp6 after long-term cultivation. Diagrams show mRNA expression levels of Bmpr1a, Bmpr1b, Bmpr2, Bmp6 and Bmp2 normalized to Eef1a. Abbreviations: aMSCs, mesenchymal stromal cells from aged donors; yMSCs, mesenchymal stromal cells from young donors; eEf1a, Elongation factor 1-alpha; Bmpr1a, Bone morphogenetic protein receptor type-1a; Bmpr1b, Bone morphogenetic protein receptor type-1b; Bmpr2, Bone morphogenetic protein receptor type-2; Bmp6, Bone morphogenetic protein 6. (n = 3) * indicates statistical significance (p<0.05).

Table S1 Antibodies used for flow cytometry.

Table S2 Primer sequences used for quantitative RT-PCR.

Table S3 Exclusively expressed mRNAs in primary MSCs of passage 2.

Table S4 Exclusively expressed mRNAs in long-term cultivated MSCs of passage 30 and 100.

Table S5 Genes with up-regulated expression after long-term cultivation.

Table S6 Genes with down-regulated expression after long-term cultivation.
Author Contributions

Conceived and designed the experiments: SG JA GK GND. Performed the experiments: SG MT JK DK OK TP. Analyzed the data: SG MT JK DK AO OK JA GK. Contributed reagents/materials/analysis tools: SG MT JK DK. Wrote the paper: SG.

References

1. Salem HK, Thiernemann C (2010) Mesenchymal stromal cells: current understanding and clinical status. Stem Cells 28: 585–596.
2. Kasper G, Glaser JD, Geisler S, Ode A, Tuischer J, et al. (2007) Matrix metalloproteinase activity is an essential link between mechanical stimulus and mesenchymal stem cell behavior. Stem Cells 25: 1915–1934.
3. Kasper G, Dantenet K, Tuischer J, Hoefi M, Gaber T, et al. (2007) Mesenchymal stem cells regulate angiogenesis according to their mechanical environment. Stem Cells 25: 903–910.
4. Krampnera M, Pizzolo G, Aprili G, Franchini M (2006) Mesenchymal stem cells for bone, cartilage, tendon and skeletal muscle repair. Bone 39: 678–683.
5. Le Blanc K, Pitarque M (2005) Mesenchymal stem cells: progress toward promise. Cytotherapy 7: 36–45.
6. Chanda D, Kumar S, Ponnazhagan S (2010) Therapeutic potential of adult bone marrow-derived mesenchymal stem cells in diseases of the skeleton. J Cell Biochem 111: 249–257.
7. Quarto R, Mastrogiacomo M, Cancrini R, Kutepov SM, Mukhachev V, et al. (2001) Repair of large bone defects with the use of autologous bone marrow stromal cells. N Engl J Med 344: 385–396.
8. Warner K, Kelly H, Doll RA, Tegtmeyer F, Einhorn TA, et al. (2006) Fracture healing in the elderly patient. Exp Gerontol 41: 1090–1093.
9. Streb B, Senturk U, Riha T, Kaspar K, Mueller E, et al. (2008) Influence of age and mechanical stability on bone defect healing: age reverses mechanical effects. Bone 42: 758–764.
10. Kasper G, Mao L, Geisler S, Draycheva A, Trippens J, et al. (2009) Insights into mesenchymal stem cell aging: involvement of antioxidant defense and actin cytoskeleton. Stem Cells 27: 1288–1297.
11. Sodhi S, Scott A, StokIng A (2006) Aging of mesenchymal stem cells. Ageing Res Rev 5: 91–116.
12. Wagner W, Ho AD, Zemke M (2010) Different facets of aging in human mesenchymal stem cells. Tissue Eng Part B 16: 445–453.
13. Rosland GV, Svendsen A, Torvik A, Sobha E, McCormack E, et al. (2009) Longitudinal culture of bone marrow-derived human mesenchymal stem cells frequently undergo spontaneous malignant transformation. Cancer Res 69: 5331–5339.
14. Wagner W, Bork S, Horn P, Krumi D, Walther T, et al. (2009) Aging and replicative senescence have related effects on human stem and progenitor cells. PLoS One 4: e5846.
15. Ode A, Kopf J, Kurz A, Schmid-Bleek K, Schrade P, et al. (2011) CD73 and CD29 concurrently mediate the mechanically induced decrease of migratory capacity of mesenchymal stromal cells. Eur Cell Mater 22: 26–42.
16. Kasper G, Reule M, Tschischmann M, Dankert N, Stout-Weider K, et al. (2007) Stromelysin-3 over-expression enhances tumourigenesis in MCF-7 and MDA-MB-231 breast cancer cell lines: involvement of the IGF-1 signalling pathway. BMC Cancer 7: 12.
17. Kasper G, Ode A, Groothing A, Glaser J, Gaber T, et al. (2010) Validation of beta-actin used as endogenous control for gene expression analysis in mesenchymal stromal cells. Stem Cells 28: 633–645.
18. Prigione A, Fauler B, Lurz R, Lehrach H, Adjaye J (2010) The senescence-related mitochondrial/oxidative stress pathway is repressed in human induced pluripotent stem cells. Stem Cells 28: 721–733.
19. Dreniz G, Sherman ET, Hoscak DA, Yang J, Gao W, et al. (2003) DAVID: Database for Annotation, Visualization, and Integrated Discovery. Genome Biol 4: P3.
20. Khosla S, Westendorf JJ, Mødder UI (2010) Concise review: Insights from mechanobiology studies: amendments. Stem Cells 28: 633–634.
21. Wagner W, Ho AD, Zenke M (2010) How to track lifetime changes. Handb Exp Pharmacol: 249–282.
22. Duda GN, Geißler S, Kasper G (2008) Tissue Engineering. In: Dietel M, Suttrop N, M Z, editors. Harrisons Innere Medizin. German Edition ed. Berlin: Springer Verlag.
23. Estrada JC, Albo C, Benguria A, Dopazo A, López-Romero P, et al. (2012) Culture of human mesenchymal stem cells at low oxygen tension improves growth and genetic stability by activating glycolysis. Cell Death Differ 19: 743–755.
24. Krampera M, Pizzolo G, Aprili G, Franchini M (2006) Mesenchymal stem cells for bone, cartilage, tendon and skeletal muscle repair. Bone 39: 678–683.
25. Krampera M, Pizzolo G, Aprili G, Franchini M (2006) Mesenchymal stem cells for bone, cartilage, tendon and skeletal muscle repair. Bone 39: 678–683.
26. Miura M, Miura Y, Padilla-Nash HM, Molinolo AA, Fu B, et al. (2006) Accumulated chromosomal instability in murine bone marrow mesenchymal stem cells is associated with replicative senescence and is accompanied by telomere shortening. Stem Cells 24: 1093–1103.
27. Iwashapan R, kaushal D, Krierch C, Tissen F, Patel B, et al. (2008) Long-term in vitro expansion alters the biology of adult mesenchymal stem cells. Cancer Res 68: 4229–4238.
54. Larsen M, Tremblay ML, Yamada KM (2003) Phosphatases in cell-matrix adhesion and migration. Nat Rev Mol Cell Biol 4: 700–711.

55. Kitaori T, Ito H, Schwarz EM, Tsutsumi R, Yoshitomi H, et al. (2009) Stromal cell-derived factor 1/CXCR4 signaling is critical for the recruitment of mesenchymal stem cells to the fracture site during skeletal repair in a mouse model. Arthritis Rheum 60: 813–823.

56. Paradies G, Petrosillo G, Paradies V, Ruggiero FM (2010) Oxidative stress, mitochondrial bioenergetics, and cardiolipin in aging. Free Radic Biol Med 48: 1286–1295.

57. Passos JF, Saretzki G, Ahmed S, Nelson G, Richter T, et al. (2007) Mitochondrial dysfunction accounts for the stochastic heterogeneity in telomere-dependent senescence. PLoS Biol 5: e110.

58. Savitha S, Panneerselvam C (2006) Mitochondrial membrane damage during aging process in rat heart: potential efficacy of L-carnitine and DL alpha lipoic acid. Mech Ageing Dev 127: 349–355.

59. Xie X, Hiona A, Lee AS, Cao F, Huang M, et al. (2011) Effects of long-term culture on human embryonic stem cell aging. Stem Cells Dev 20: 127–130.

60. Hansford RG, Hogue RA, Mildazaine V (1997) Dependence of H2O2 formation by rat heart mitochondria on substrate availability and donor age. J Bioenerg Biomembr 29: 89–95.