

# Microgravity Reduces the Differentiation and Regenerative Potential of Embryonic Stem Cells

Elizabeth A. Blaber,<sup>1,2</sup> Hayley Finkelstein,<sup>1</sup> Natalya Dvorochkin,<sup>1</sup> Kevin Y. Sato,<sup>3</sup>  
Rukhsana Yousuf,<sup>1</sup> Brendan P. Burns,<sup>2,4</sup> Ruth K. Globus,<sup>1</sup> and Eduardo A.C. Almeida<sup>1</sup>

Mechanical unloading in microgravity is thought to induce tissue degeneration by various mechanisms, including inhibition of regenerative stem cell differentiation. To address this hypothesis, we investigated the effects of microgravity on early lineage commitment of mouse embryonic stem cells (mESCs) using the embryoid body (EB) model of tissue differentiation. We found that exposure to microgravity for 15 days inhibits mESC differentiation and expression of terminal germ layer lineage markers in EBs. Additionally, microgravity-unloaded EBs retained stem cell self-renewal markers, suggesting that mechanical loading at Earth's gravity is required for normal differentiation of mESCs. Finally, cells recovered from microgravity-unloaded EBs and then cultured at Earth's gravity showed greater stemness, differentiating more readily into contractile cardiomyocyte colonies. These results indicate that mechanical unloading of stem cells in microgravity inhibits their differentiation and preserves stemness, possibly providing a cellular mechanistic basis for the inhibition of tissue regeneration in space and in disuse conditions on earth.

## Introduction

ON EARTH, ORGANISMS ARE constantly subjected to gravity-generated forces [1] that provide an array of mechanical stimulation essential for normal cell and tissue function. The influence of gravity-generated forces on the human body is especially evident in the effects of physical exercise on the skeleton. Specifically, mechanical loading of tissues promotes tissue regenerative health via stimulation of adult stem cell proliferation and differentiation. On the other hand, mechanical unloading experienced during spaceflight-induced microgravity ( $\mu$ g) conditions, and other disuse conditions including prolonged bedrest, induce degenerative changes in physiology, including tissue regenerative deficits and tissue loss, such as observed in bone and muscle. Because of this, it is important to understand mechanical unloading-mediated changes in stem cells that may result in altered tissue regenerative health.

Stem cells derived from all three germ layers are known to be affected by  $\mu$ g, including cells originating from the ectoderm lineage with a decreased capacity to differentiate into immune cells [2], cells from the mesoderm lineage (hematopoietic stem cells) with a diminished capacity to differentiate into blood tissue [3], and endoderm-derived tissues such as the lungs and pancreas [4]. The rate of stem cell-based

regeneration, however, is tissue-specific and highly variable—ranging from renewal of intestinal epithelial cells every 2 or 3 days, to about 120 days for red blood cells, to very slow renewal rates of years in cells such as cardiomyocytes [5,6]. Because of the widely variable tissue-specific regenerative renewal times,  $\mu$ g is likely to affect regeneration at different rates, with different physiological outcomes.

While several studies have investigated the role of increased mechanical load in promoting cell proliferation and differentiation [7–9], few have investigated the effects of removing that load in  $\mu$ g. Some studies using “simulated microgravity” (SMG) have investigated its impact on embryonic stem cell (ESC) properties, including cell numbers, adhesion capabilities and apoptosis rates [10], and differentiation into periodontal ligament cells [11], and liver stem cells [12]. However, while SMG-generating devices, such as the rotating wall vessel (RWV) and random positioning machine (RPM), may randomize the gravity vector, they do not reduce the overall mechanical stimulation from fluid flow shear and hydrostatic pressure that adherent cells experience in these vessels, thus limiting the value and accuracy of the models.

Previously, we have described mechanical unloading-associated stem cell regenerative alterations in bone from mice exposed to  $\mu$ g [13,14] and are now studying mechanistic

<sup>1</sup>Space Biosciences Division, NASA Ames Research Center, Moffett Field, California.

<sup>2</sup>School of Biotechnology and Biomolecular Sciences, University of New South Wales, Sydney, Australia.

<sup>3</sup>FILMSS Wyle, Space Biology, NASA Ames Research Center, Moffett Field, California.

<sup>4</sup>Australian Centre for Astrobiology, University of New South Wales, Sydney, Australia.

aspects of these findings using a model of early lineage commitment during mouse embryonic stem cell (mESC) early differentiation into embryoid bodies (EBs). When mESCs are maintained on a gelatin matrix with the pluripotency factor leukemia inhibitory factor (LIF), or in the presence of an embryonic fibroblast feeder layer, these cells remain pluripotent. However, when the cells are removed from contact with the feeder layer, or when LIF is removed from the culture medium in combination with growing the mESCs on ultra-low adhesion substrates, mESCs form three-dimensional spherical cell aggregates, known as EBs, and begin to spontaneously differentiate [15,16].

As EB differentiation continues, the cells follow a reproducible temporal pattern that recapitulates early embryogenesis although without organized patterning of tissues and organs [15,16]. Over time, EBs increase in cell number and complexity as cells form structures comparable to embryonic germ layers including a wide variety of cell types, such as, cardiomyocytes, hematopoietic cells, and neurons [17–19]. Although EB formation specifically models stem cell differentiation into embryonic tissues, this process has significant similarities with adult stem cell-based tissue regeneration [20], thus EBs have a broad utility to investigate the effects of mechanical unloading on adult tissue regenerative processes, too.

Here, we report results from using the EB stem cell differentiation model to study mESC early lineage commitment in  $\mu\text{g}$  in the NASA Space Tissue Loss (STL) experiment performed on the Space Shuttle Discovery during the NASA STS-131 mission. Our broad hypothesis underlying this experiment is that mechanical unloading of cells and tissues in  $\mu\text{g}$  alters the proliferation and differentiation patterns of stem cells resulting in decreased stem cell-based tissue regenerative potential in space. In this study, we found that spaceflight in  $\mu\text{g}$  promoted the maintenance of EB stem cell gene expression and post- $\mu\text{g}$  reloading differentiation potential, defined as “stemness”, and inhibited the appearance of differentiation markers for multiple tissue lineages. These findings may have important implications for the maintenance of tissue regenerative health in both astronauts during short and long-duration spaceflight in  $\mu\text{g}$  conditions, and for humans on earth.

## Experimental Procedures

### *mESC culture*

mESCs were cultured on 10 cm tissue culture treated dishes coated with 0.1% gelatin. Cells were cultured in mESC medium (DMEM supplemented with 15% FBS, 4 mM L-glutamine, 1 $\times$  nonessential amino acids, 1 mM sodium pyruvate, 1% antibiotic solution (penicillin/streptomycin), trace  $\beta$ -mercaptoethanol, and 10 ng/mL LIF. The medium was changed daily and cells were passaged every 48 h using 0.25% trypsin solution.

### *mESC differentiation–formation of embryoid bodies*

Before differentiation  $5.0 \times 10^6$  mESCs were removed and fixed in RNAlater II to serve as a baseline control for gene expression analysis. To form EBs, 59 h before spaceflight LIF was removed from the mESC culture media and cells were passaged using 0.25% trypsin solution and

transferred to ultra low adhesion 10 cm tissue culture dishes, thereby preventing reattachment of cells. A seeding density of  $5.8 \times 10^6$  mESC per dish was used. Half of the medium was changed after 24 h to prevent loss of cell density.

### *Spaceflight*

*Cell culture module.* The STL experiment was conducted within the Cell Culture Module (CCM; Tissue Genesis, Inc.) hardware in a middeck locker on the space shuttle. The CCM is a fully automated system and provides gas perfusion, medium recirculation, and medium routing by peristaltic pumps and pinch valves, reagent injection (RNAlater II), and sample collection. Cells were cultured within hollow fiber bioreactors (Spectrum Labs), which allowed full submersion of the cells in the extra-capillary space (ECS) with 60 mL of medium recirculating through the intracapillary space. Medium nutrients diffused through the hollow fibers protecting cells from fluid flow shear forces that would otherwise negate the low mechanical loading of the  $\mu\text{g}$  environment. Bioreactors were primed with isopropanol for 10 min, washed with sterile water and stored in phosphate buffered saline (PBS). Bioreactors were also coated with 0.2% bovine serum albumin in PBS for 3 h at 37°C to prevent cell attachment. CCM flow paths were primed and operated with cell culture medium for 24–48 h. Fresh medium was replaced immediately before EB loading. Materials used in the fluid flow path included platinum-cured silicone tubing for CO<sub>2</sub> supply, pharmed tubing, and Hyclone medium bags.

*STS-131 STL.* At 24 h before launch, EBs were transferred from ultra low adhesion plates to 24 bioreactors plus spares, with one plate being loaded into each bioreactor. Bioreactors were integrated into the CCM for spaceflight ( $n=12$ ), and into a separate CCM for synchronous ground controls ( $n=12$ ). The spaceflight CCM was integrated into the space shuttle orbiter middeck locker 19 h before launch. The STL payload was flown during the STS-131 mission on the space shuttle Discovery (OV-103), which was launched on 5th April 2010 and landed on the 20th April 2010. The synchronous ground control unit was maintained at Kennedy Space Center under identical conditions to the spaceflight CCM except for exposure to  $\mu\text{g}$ . Four ground and four flight bioreactors were automatically fixed with 55 mL of RNAlater II 28 h before landing.

### *Postflight analysis of metabolic activity*

Cell culture medium was collected 3 h postlanding from both the medium reservoirs and bioreactor ECS (1xg,  $n=5$ ;  $\mu\text{g}$ ,  $n=8$ ). Glucose consumption and lactate production were measured using an i-STAT handheld blood analyzer using G and CG4+ cartridges.

### *Postflight embryoid body culture*

Bioreactors were opened 3 h postlanding and equal volumes of EB suspensions were placed on 22 mm coverslips with either collagen or fibronectin and cultured for 9 days, or on 10 cm tissue culture treated dishes (1xg,  $n=5$ ;  $\mu\text{g}$ ,  $n=8$ ). After 24 h, numbers of adherent EBs were quantified with light microscopy. Following 9 days of culture, colonies of contractile cells were identified and quantified with light microscopy. Cells were then washed with PBS and fixed in 4% paraformaldehyde on ice.

### Embryoid body viability

To determine viability EBs were stained for 30 min with 0.5  $\mu$ M calcein and 1  $\mu$ M ethidium homodimer and imaged with fluorescence microscopy.

### RNA isolation

EBs in RNAlater II were collected through a 40  $\mu$ m sieve and placed in TRIzol reagent for RNA isolation. Samples were then purified using an RNeasy Mini Kit with added Genomic DNA Elimination step (Qiagen) according to the manufacturer's protocol ( $n=4$ ). RNA concentrations were measured using spectrophotometry (Nanodrop) and quality was determined by agarose gel electrophoresis.

### Real time quantitative polymerase chain reaction analysis

To determine gene expression alterations in EBs differentiated in  $\mu$ g compared to 1xg, Qiagen pathway-focused real time quantitative polymerase chain reaction (RT-qPCR) arrays were used. We specifically analyzed EBs exposed to spaceflight and fixed before Orbiter reentry (FLT) and EBs maintained on the ground at 1xg (GC) fixed at the same time as FLT samples and baseline mESCs that were preserved before EB formation. Arrays related to stem cells, the p53 pathway, and tissue lineage markers were examined and each pathway-focused array consisted of primer sets for 84 genes of interest, five reference genes (Gusb, Hprt1, Hsp90ab1, Gapdh, and Actb), one genomic DNA contamination control, three positive polymerase chain reaction

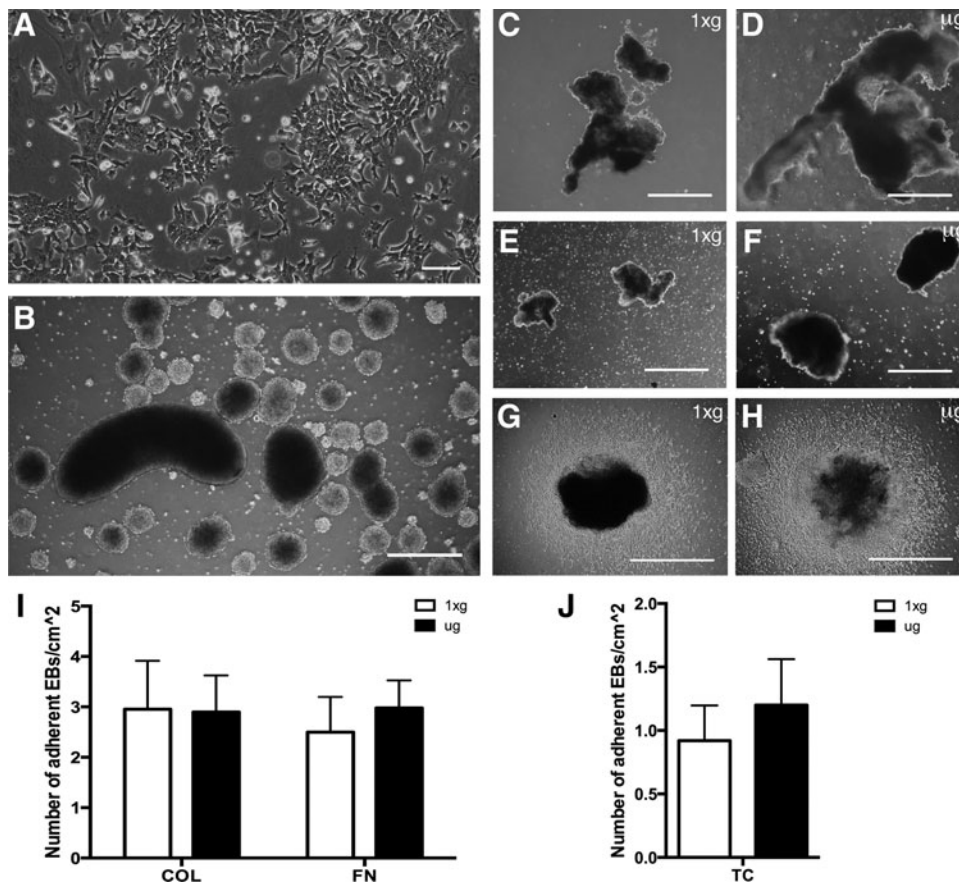
(PCR) controls, and three positive reverse transcription controls, on a 96-well plate.

For each sample, 0.1 microgram RNA was reverse transcribed into cDNA using RT<sup>2</sup> PreAMP cDNA Synthesis Kit (Qiagen) according to the manufacturer's protocol. The cDNA was then mixed with RT<sup>2</sup> SYBR Green/Rox qPCR master mix and 25  $\mu$ L was added to each well of the PCR plate. The plates were sealed with optical thin-walled 8 cap strips and RT-qPCR of sample arrays was performed using an Applied Biosystems 7500 Real Time PCR instrument. RT-qPCR conditions were as follows: one cycle 95°C for 10 min, 40 cycles of 95°C for 15 s and 60°C for 1 min, followed by one cycle of 95°C for 15 s, 60°C for 1 min, 95°C for 15 s, and 60°C for 15 s. Gene expression levels from all arrays were analyzed for alterations in expression levels as compared to controls ( $n=4$ ,  $P<0.05$ ) using a PCR Array Data Analysis Template (v3.2; SABiosciences). Data analysis was based on the  $\Delta\Delta$ Ct method and gene expression levels were normalized to four reference genes (Gusb, Hprt1, Gapdh, and Actb).

## Results

### Post- $\mu$ g embryoid body viability and adhesion

EBs were either fixed on orbit with RNAlater II or returned live to earth following 15 days in  $\mu$ g. EBs returned to earth live and corresponding 1xg controls were plated on either collagen (COL)- or fibronectin (FN)-coated 22 mm cover slips and 10 cm tissue cultures (TC) dishes within 4 h of the orbiter landing. Both  $\mu$ g and 1xg EBs adhered similarly to COL and FN matrices or TC-treated plastic. Specifically, the number of

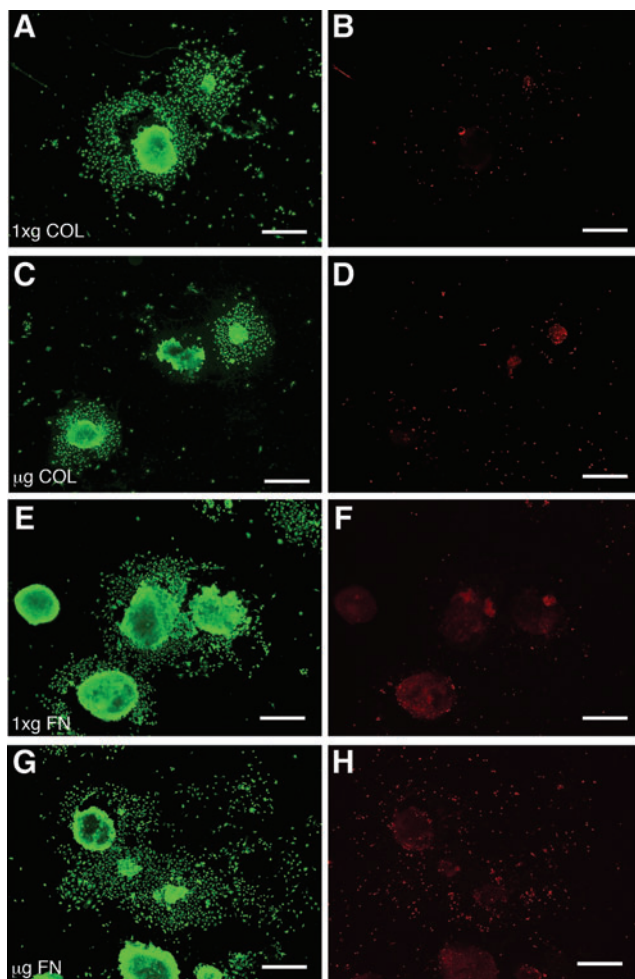


**FIG. 1.** Embryoid body (EB) formation and recovery post- $\mu$ g exposure. mESCs (A) were used to form EBs (B) for analysis of early lineage commitment and differentiation during and after 15 days spaceflight. EBs from 1xg bioreactor controls (C, E) and those recovered post- $\mu$ g exposure (D, F) showed similar appearance both in large sheets adherent to bioreactor fibers (C, D) and in smaller more EB-like cell clusters (E, F). No significant differences were found in the number of EBs that were recovered and adhered to collagen, COL, fibronectin, FN (I) and tissue culture-treated plastic, TC (J) matrices following differentiation in  $\mu$ g (H) compared to 1xg; (G) conditions. Scale bar=100  $\mu$ m (A) or 500  $\mu$ m (B-H). 1xg,  $n=5$ ;  $\mu$ g  $n=8$ . 1xg, Earth's gravity; mESC, mouse embryonic stem cell;  $\mu$ g, microgravity; TC, tissue cultures.

adherent EBs 150  $\mu\text{m}$  in diameter or larger were counted, with no differences in adhesion observed (Fig. 1). Cell viability in adherent EBs and their outgrowth was determined with calcein AM and ethidium homodimer. No differences were found in the viability of EBs cultured in  $\mu\text{g}$  compared to those cultured at 1xg, with cultures in all matrix conditions displaying  $\sim 95\%$  viability (Fig. 2). For EBs preserved with RNAlater II in  $\mu\text{g}$ , it was not possible to determine viability before automated injection of the preservative; however, since they were grown under identical conditions to the live-returned EBs, we expect similar viability.

### Post- $\mu\text{g}$ metabolic activity

Glucose present in the culture medium was measured immediately before launch and within 4 h of landing. Glucose concentration in  $\mu\text{g}$  and 1xg control bioreactors upon loading of EBs was identical (3.6 g/L). Following 15 days



**FIG. 2.** Cells in EBs differentiated in  $\mu\text{g}$  showed no alterations in viability after 24 h outgrowth on either collagen or fibronectin matrices. Cell outgrowths from EBs adhering to collagen, COL (A–D) or fibronectin, FN (E–H) matrices 24 h following recovery from  $\mu\text{g}$  (C–D, G–H) and 1xg conditions (A–B, E–F) showed no significant differences in numbers of live viable cells (green fluorescence, calcein AM) or dead cells (red fluorescence, ethidium homodimer). Scale bar = 500  $\mu\text{m}$ . 1xg,  $n=5$ ;  $\mu\text{g}$ ,  $n=8$ . Color images available online at [www.liebertpub.com/scd](http://www.liebertpub.com/scd)

glucose concentration in  $\mu\text{g}$  bioreactors was on average 1.56 g/L, and 1.94 g/L in 1xg controls, indicating that EBs differentiated at 1xg consumed an average of 65.20% of glucose, while in  $\mu\text{g}$  EBs only consumed an average of 56.89% ( $P < 0.01$ ). No significant alterations in lactate production were observed (15.96 and 17.96 mM average respectively,  $P = 0.259$ ). Although production of lactate by EBs differentiated in  $\mu\text{g}$  was slightly lower than 1xg control production, both values are in a normal physiological range.

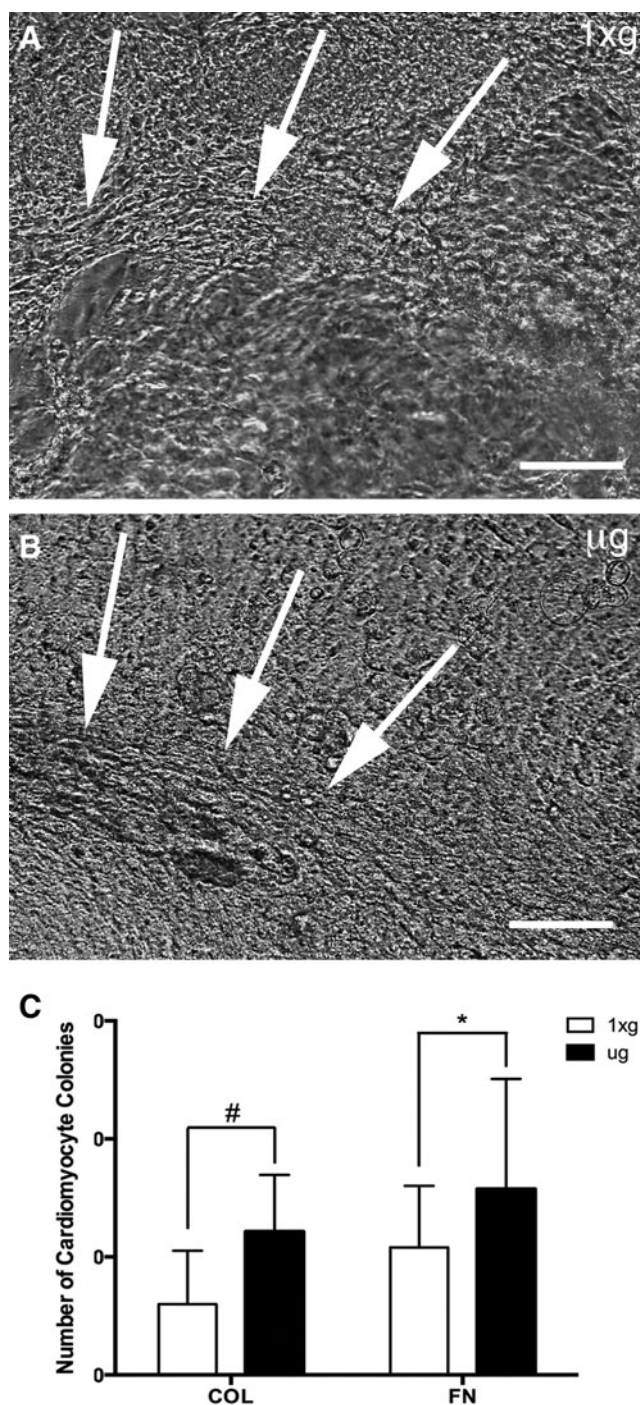
### Post- $\mu\text{g}$ cardiomyocyte differentiation

Following return to 1xg conditions, live EBs were placed on collagen or fibronectin matrices, and cells in EBs were allowed to migrate onto the ECM substrate for 9 days in an outgrowth assay. Cells in EBs still capable of outward migration are thought of being less differentiated and can provide a measure of the remaining earlier-stage progenitor or stem cell populations in EBs. In addition, during outgrowth new contractile cardiomyocyte colonies formed spontaneously, and were quantified to evaluate the remaining “stemness” of EBs following  $\mu\text{g}$  exposure. EBs differentiated in  $\mu\text{g}$  showed an average of 12.14 contractile colonies per 22 mm collagen matrix-coated coverslip, and 15.75 colonies on fibronectin, while ground controls only yielded an average of 7.77 and 6.08 colonies respectively ( $P < 0.01$  and  $P < 0.05$ , Fig. 3). These results indicated that cells from post- $\mu\text{g}$  EB outgrowths exhibited approximately twice the potential to differentiate into cardiomyocytes upon reloading at 1xg, as controls. This finding suggests that  $\mu\text{g}$  caused either a greater degree of stem cell pluripotency, greater numbers of stem cells, or a combination of both.

### Microgravity embryoid body gene expression

To further investigate the hypothesis that EBs maintained greater stemness in  $\mu\text{g}$ , we conducted RT-qPCR on cells preserved on-orbit after 15 days in  $\mu\text{g}$  and analyzed over 250 genes of interest related to (1) ESC signaling and stem cell markers, (2) terminal, lineage-specific markers, and (3) the cell cycle and p53-signaling pathway. Automated on-orbit fixation ensured that any effects of reloading on the cells during orbiter reentry and landing were excluded. To determine the extent of differentiation, the gene expression profile of the 1xg control EBs was compared to that of the  $\mu\text{g}$  EBs and to the baseline undifferentiated mESCs. RT-qPCR gene arrays showed that out of 252 genes investigated, the majority showed two-fold or greater differences in expression level between EB differentiation-associated changes at 1xg compared to  $\mu\text{g}$  (Figs. 4–6, Table 1).

*Gene expression alterations associated with stem cell signaling pathways.* Growth in  $\mu\text{g}$  caused alterations in the Notch and Wnt stem cell signaling pathways including altered expression of NUMB (–2.45-fold,  $P < 0.01$ ), DLL1 and DLL3 (1.67 and 3.85-fold respectively,  $P < 0.5$ ), and DVL1 (–2.5-fold,  $P < 0.01$ ) in EBs differentiated in  $\mu\text{g}$  compared to EBs differentiated at 1xg (Fig. 4A). Large increases in WNT1 were also found in  $\mu\text{g}$  samples compared to undifferentiated mESCs (81.91-fold,  $P < 0.05$ ) and a smaller increase (not significant) in 1xg samples compared to undifferentiated mESCs (26.05-fold,  $P = 0.091$ ). Decreased expression of FZD1 (–2.50-fold,



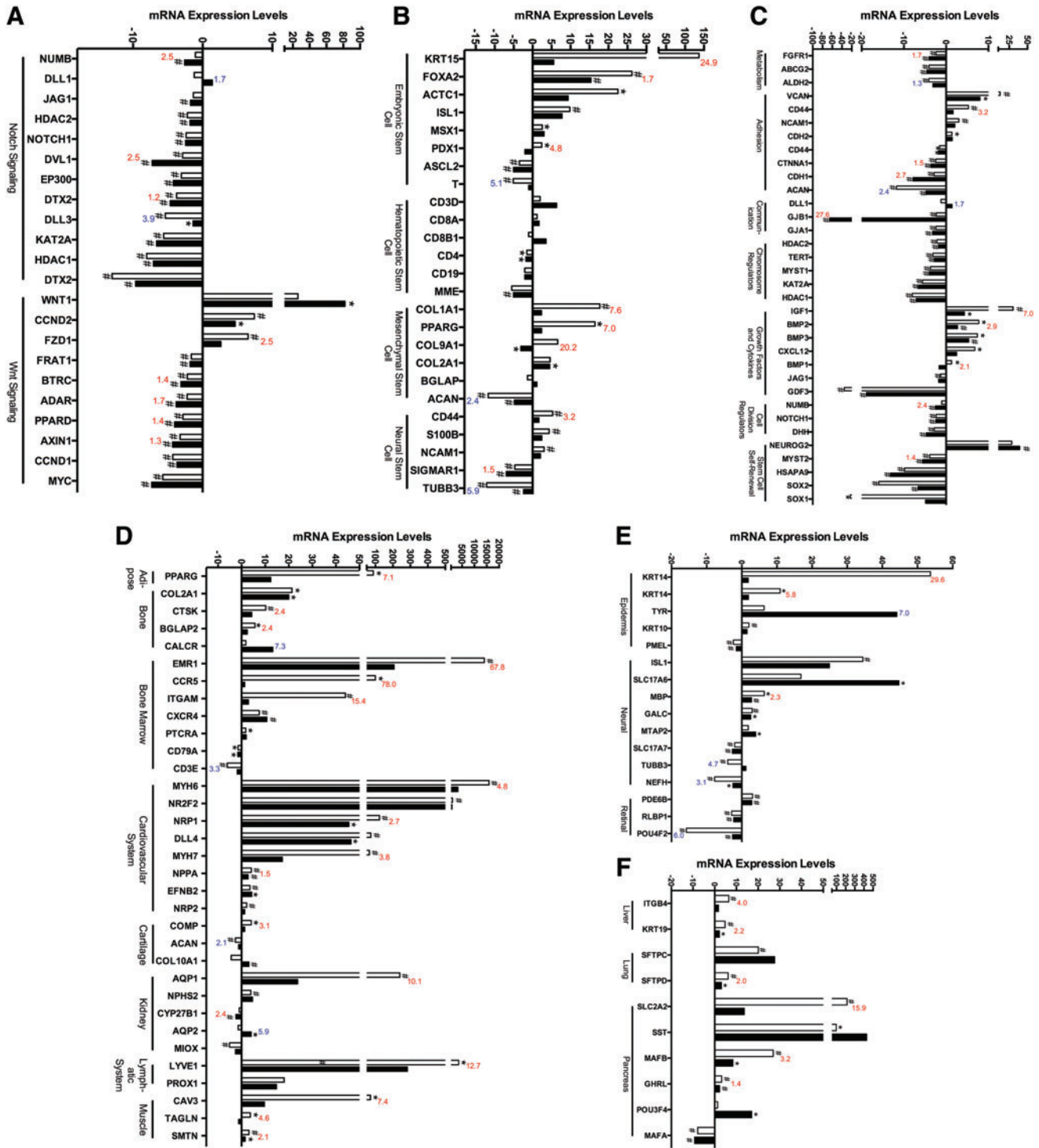
**FIG. 3.** EBs differentiated in  $\mu\text{g}$  showed increased differentiation potential following reloading at 1xg. Nine-day post- $\mu\text{g}$  cell outgrowths from EBs differentiated in  $\mu\text{g}$  (**B**) showed increased numbers of contractile cardiomyocyte colonies (**C**) compared with ground control cultures (**A**). Arrows indicate contractile region of the EB outgrowth. Scale bar = 100  $\mu\text{m}$ . 1xg,  $n=5$ ;  $\mu\text{g}$ ,  $n=8$ ; # $P<0.01$ , \* $P<0.05$ .

$P<0.01$ ) and ADAR (−1.70-fold,  $P<0.01$ ) were also found in  $\mu\text{g}$  samples compared to 1xg controls.

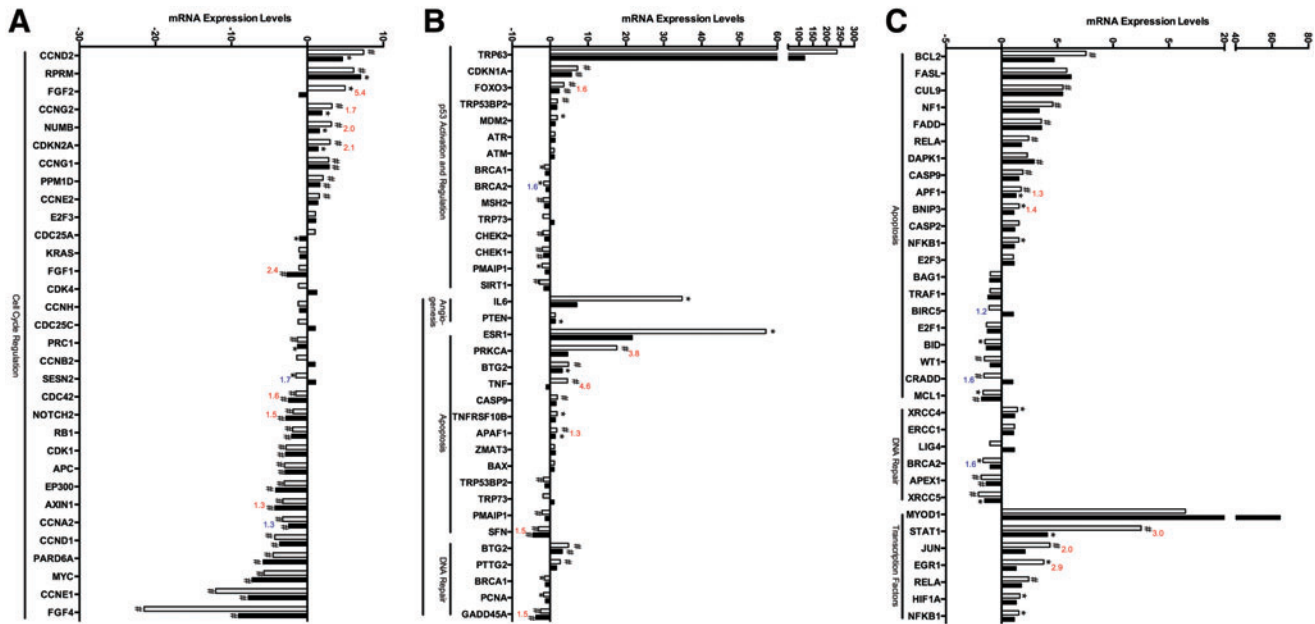
Genes associated with the hematopoietic, mesenchymal, embryonic, and neural stem cell lineages were also investigated (Fig. 4B, Table 1). Microgravity downregulated a

number of ESC markers including KRT15 (−24.9-fold,  $P<0.05$ ), FOXA2 (−1.7-fold,  $P<0.01$ ), and PDX1 (−4.8-fold,  $P<0.05$ ). EBs differentiated at 1xg had increased expression of ACTC1 compared with undifferentiated mESCs (22.48-fold,  $P<0.01$ ), while  $\mu\text{g}$  samples showed a lower level of expression than 1xg controls (9.347, not significant), as did ASCL2 (−3.49 and −5.04 respectively,  $P<0.01$ , Fig. 4B, Table 1). Decreased expression of the hematopoietic stem cell marker CD3D was also observed in both 1xg and  $\mu\text{g}$  samples compared with undifferentiated mESCs (−1.53 and −1.77 respectively,  $P<0.05$ ) and in MME (−5.50 and −5.02 respectively,  $P<0.01$ ). Mesenchymal stem cell markers also showed significant alterations, including COL1A1 (−7.6-fold,  $P<0.05$ ), PPAR $\gamma$  (−7.0-fold,  $P<0.05$ ), and COL9A1 (−20.2-fold,  $P<0.05$ , Fig. 4B, Table 1). The neural stem cell marker TUBB3 showed increased expression in  $\mu\text{g}$  samples compared with 1xg controls (5.9-fold,  $P<0.05$ , Fig. 4B, Table 1), and decreased expression of CD44 in  $\mu\text{g}$  samples compared with 1xg control (3.2-fold,  $P<0.05$ ).

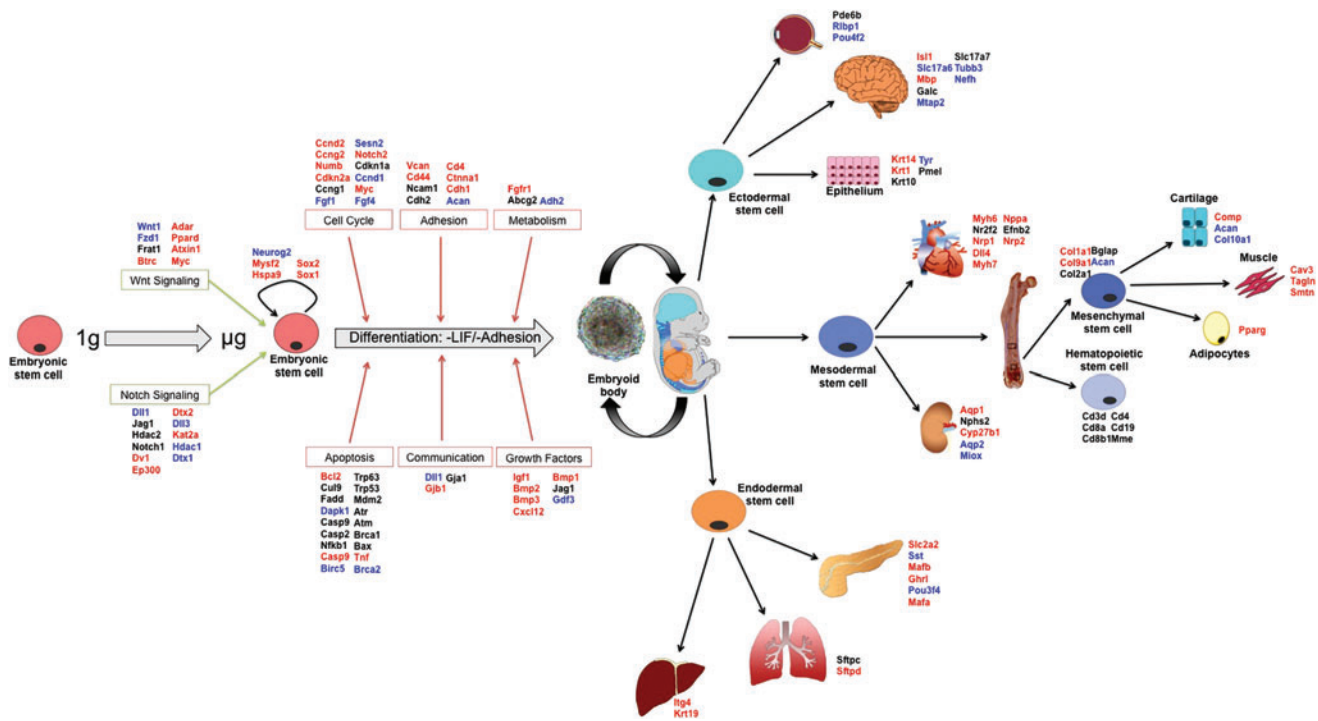
*Gene expression alterations in stem cell properties.* Stem cell-specific gene expression markers associated with cell division, self-renewal, adhesion, cell–cell communication, and metabolism were also investigated. The expression of several metabolic genes, including ALDH2, ABCG2, and FGFR1 decreased in 1xg controls compared with undifferentiated mESCs (−4.41, −4.06, and −2.42 respectively,  $P<0.01$ , Fig. 4C, Table 1). These genes also showed decreased expression in  $\mu\text{g}$  samples compared with undifferentiated mESCs (−3.14, −4.56, and −4.04 respectively,  $P<0.01$ ) indicating that cell growth was not inhibited by spaceflight conditions. Expression of several cell adhesion molecules decreased in both  $\mu\text{g}$ - and 1xg-differentiated EBs compared with undifferentiated mESCs (Fig. 4C, Table 1). However, ACAN, an extracellular matrix protein in cartilaginous tissue, had increased expression in flight samples compared with ground samples and CDH2 had decreased expression. Furthermore, expression of NCAM1 and CD44 increased in 1xg samples compared with undifferentiated mESCs (3.01 and 5.30-fold change respectively,  $P<0.01$ ) but their expression in  $\mu\text{g}$ -differentiated EBs did not change significantly compared to mESCs (2.034-fold change,  $P=0.103$ , and 1.629-fold change,  $P=0.231$  respectively, Fig. 4C, Table 1). Significant alterations in cell–cell communication molecules (Fig. 4C, Table 1) were found. Specifically, GJB1 exhibited significantly decreased expression in  $\mu\text{g}$  samples (−65.49,  $P<0.01$ ) compared with undifferentiated mESCs and compared directly to EBs differentiated at 1xg (−27.64,  $P<0.01$ ). Growth factors and cytokines associated with stem cell differentiation, including IGF1, BMP2 and BMP3, and CXCL12 were found to be increased in EBs differentiated at 1xg compared with undifferentiated mESCs (30.25, 7.73, 7.38, and 6.77-fold respectively,  $P<0.05$ ), but these had decreased expression in EBs differentiated in  $\mu\text{g}$  [4.30, 2.70, 5.33, and 2.47 (not significant) respectively,  $P<0.05$ , Fig. 4C]. Importantly, markers for stem cell self-renewal (eg, Neurog2, Sox1, and Sox2) were found to be decreased in EBs differentiated in normal 1xg conditions, while these markers were increased in EBs differentiated in  $\mu\text{g}$  conditions, possibly indicating that cells remained in a stem cell-like state rather than undergoing differentiation.



**FIG. 4.** EBs differentiated in  $\mu\text{g}$  showed altered expression of stem cell-specific markers and stem cell signaling molecules and decreased expression of terminal differentiation markers. Real time quantitative polymerase chain reaction (RT-qPCR) expression of EBs differentiated in  $\mu\text{g}$  showed alterations in genes associated with the Notch and Wnt stem cell signaling pathways (A), markers for stem cell lineages (B), and stem cell-specific markers for metabolism, adhesion, communication, and self-renewal (C). Furthermore, terminal differentiation markers showed significant alterations for all three germ layers—mesoderm (D), ectoderm (E), and endoderm (F). Bars indicate gene expression of 1xg- (white) and  $\mu\text{g}$ -differentiated (black) EBs compared to undifferentiated mESCs. Numbers indicate up- (blue) or downregulation (red) of the specified gene in  $\mu\text{g}$  samples compared to 1xg controls.  $n=4$ ,  $*P<0.05$ ,  $\#P<0.01$ . Color images available online at [www.liebertpub.com/scd](http://www.liebertpub.com/scd)



**FIG. 5.** Spaceflight altered the expression of genes associated with the cell cycle and p53 signaling pathway. RT-qPCR analysis of cells differentiated in  $\mu$ g showed key alterations in molecules associated with the cell cycle (A), activation and regulation of p53 and p53 targets (B), and p53 downstream responses (C). Bars indicate gene expression of 1xg- (white) and  $\mu$ g-differentiated (black) EBs compared to undifferentiated mESCs. Numbers indicate up- (blue) or downregulation (red) of the specified gene in  $\mu$ g samples compared to 1xg controls.  $n=4$ , \* $P<0.05$ , # $P<0.01$ . Color images available online at [www.liebertpub.com/scd](http://www.liebertpub.com/scd)



**FIG. 6.** Diagrammatic representation of gene expression results from STL1. Differentiation of EBs during  $\mu$ g revealed a broad downregulation in gene expression of both tissue-specific stem cell markers and terminal lineage differentiation markers. Furthermore, markers for stem cell signaling, cell cycle, adhesion, and growth factors were predominantly downregulated while most apoptosis markers remained unchanged in  $\mu$ g samples compared to controls. EBs differentiated in  $\mu$ g appeared to initiate the differentiation process but fail to express normal terminal differentiation markers expressed in mechanically loaded tissues. Blue indicates upregulation, red indicates downregulation, and black indicates no change. Color images available online at [www.liebertpub.com/scd](http://www.liebertpub.com/scd)

TABLE 1. REAL TIME QUANTITATIVE POLYMERASE CHAIN REACTION ANALYSIS OF GENES ASSOCIATED WITH STEM CELL PLURIPOTENCY, LINEAGE DIFFERENTIATION, AND THE CELL CYCLE

Category	Symbol	mESC -> GC		mESC -> FLT		Changes in fold change of GC vs. FLT	GC -> FLT		
		Fold D	P value	Fold D	P value		Fold D	P value	
Stem cell-specific markers and stem cell signaling									
Signaling pathways	Notch	Dll1	-1.21	0.349	1.38	0.114	2.596	1.68	0.041
		Dll3	-5.36	<u>3.87E-05</u>	-1.38	<u>0.035</u>	3.975	3.87	<u>3.11E-04</u>
		Dtx1	-13.01	<u>3.88E-06</u>	-9.63	<u>3.68E-05</u>	3.379	1.35	0.406
		Dtx2	-3.75	<u>8.26E-07</u>	-4.65	<u>3.92E-07</u>	-0.904	-1.24	<u>0.010</u>
		Dvl1	-2.90	<u>1.19E-04</u>	-7.24	<u>3.84E-06</u>	-4.341	-2.50	<u>0.005</u>
		Ep300	-3.05	<u>1.31E-06</u>	-4.20	<u>4.54E-06</u>	-1.148	-1.38	0.054
		Hdac1	-8.04	<u>1.25E-06</u>	-7.08	<u>1.03E-07</u>	0.966	1.14	0.734
		Hdac2	-2.20	<u>9.23E-06</u>	-1.82	<u>0.001</u>	0.379	1.21	0.120
		Jag1	-1.33	0.050	-1.75	<u>0.002</u>	-0.418	-1.31	0.106
		Kat2a	-5.62	<u>7.56E-07</u>	-6.63	<u>1.39E-07</u>	-1.011	-1.18	0.314
	Wnt	Notch1	-2.38	<u>6.00E-04</u>	-2.46	<u>4.65E-06</u>	-0.077	-1.03	0.715
		Numb	-1.04	0.879	-2.59	<u>6.76E-05</u>	-1.546	-2.48	<u>0.002</u>
		Adar	-2.24	<u>4.74E-05</u>	-3.80	<u>6.04E-07</u>	-1.564	-1.70	<u>0.002</u>
		Axin1	-3.25	<u>6.26E-06</u>	-4.31	<u>2.76E-06</u>	-1.062	-1.33	<u>0.032</u>
		Btrc	-2.20	<u>1.13E-04</u>	-3.11	<u>1.85E-06</u>	-0.906	-1.41	<u>0.013</u>
		Ccnd1	-4.29	<u>8.01E-06</u>	-3.69	<u>5.76E-06</u>	0.606	1.16	0.467
		Ccnd2	7.41	<u>0.002</u>	4.64	<u>0.033</u>	-2.761	-1.59	0.168
		Frat1	-1.63	<u>0.002</u>	-1.80	<u>8.90E-05</u>	-0.169	-1.10	0.343
		Fzd1	6.51	<u>2.77E-04</u>	2.60	0.064	-3.909	-2.50	<u>0.005</u>
		Myc	-5.73	<u>0.001</u>	-7.32	<u>3.17E-04</u>	-1.592	-1.28	0.218
Stem cell differentiation marker	Embryonic cell lineage	Ppard	-2.83	<u>1.97E-05</u>	-4.04	<u>2.03E-05</u>	-1.205	-1.43	<u>0.029</u>
		Wnt1	26.05	0.091	81.91	<u>0.029</u>	55.857	3.14	0.065
		Actc1	22.48	<u>0.010</u>	9.35	0.093	-13.133	-2.41	0.358
		Ascl2	-3.49	<u>0.007</u>	-5.04	<u>0.005</u>	-1.548	-1.44	0.300
		Foxa2	26.18	<u>0.001</u>	15.37	<u>3.55E-04</u>	-10.818	-1.70	<u>0.022</u>
	Hematopoietic stem cells	Isl1	9.83	<u>0.001</u>	7.74	0.078	-2.082	-1.27	0.868
		Krt15	137.32	0.068	5.53	0.135	-131.783	-24.82	<u>0.038</u>
		Msx1	2.52	<u>0.029</u>	2.98	0.051	0.460	1.18	0.506
		Pdx1	2.42	<u>0.023</u>	-2.00	0.221	-4.417	-4.83	<u>0.006</u>
		T	-5.13	<u>0.001</u>	-1.00	0.840	4.127	5.11	<u>0.005</u>
Mesenchymal stem cells	Cd19	-2.06	0.141	-2.04	0.601	0.021	1.01	0.563	
	Cd3d	1.98	0.510	6.31	0.452	4.323	3.18	0.285	
	Cd4	-1.53	<u>0.043</u>	-1.77	<u>0.045</u>	-0.247	-1.16	0.468	
	Cd8a	1.17	0.353	1.67	0.366	0.503	1.43	0.358	
	Cd8b1	-1.05	0.950	3.51	0.422	4.566	3.70	0.352	
Neural stem cells	Mme	-5.49	<u>3.96E-06</u>	-5.02	<u>4.94E-06</u>	0.465	1.09	0.605	
	Acan	-11.72	<u>7.52E-09</u>	-4.80	<u>8.52E-06</u>	6.923	2.44	<u>0.011</u>	
	Bglap	-1.36	0.057	1.11	0.613	2.468	1.51	0.334	
	Col1a1	17.71	<u>0.006</u>	2.33	0.206	-15.378	-7.60	<u>0.012</u>	
	Col2a1	4.59	0.052	4.47	<u>0.027</u>	-0.114	-1.03	0.855	
Neural stem cells	Col9a1	6.59	0.087	-3.07	<u>0.042</u>	-9.662	-20.24	<u>0.036</u>	
	Pparg	16.44	<u>0.020</u>	2.35	0.179	-14.095	-7.01	<u>0.014</u>	
	Cd44	5.28	<u>1.12E-04</u>	1.63	0.231	-3.650	-3.24	<u>0.002</u>	
	Ncam1	3.01	<u>0.007</u>	2.03	0.103	-0.975	-1.48	0.245	
	S100b	4.36	<u>0.001</u>	2.41	0.138	-1.953	-1.81	0.111	
Neural stem cells	Sigmar1	-4.70	<u>1.99E-08</u>	-6.95	<u>6.27E-09</u>	-2.243	-1.48	<u>0.001</u>	
	Tubb3	-12.13	<u>1.94E-07</u>	-2.38	<u>3.03E-04</u>	9.747	5.09	<u>0.001</u>	

(continued)



TABLE 1. (CONTINUED)

Category	Symbol	mESC -> GC		mESC -> FLT		Changes in fold change of GC vs. FLT	GC -> FLT		
		Fold D	P value	Fold D	P value		Fold D	P value	
Stem cell-specific markers	Metabolic	<b>Abcg2</b>	<b>-4.06</b>	<b>1.39E-07</b>	<b>-4.56</b>	<b>5.98E-08</b>	<b>-0.499</b>	-1.12	0.208
		<b>Aldh2</b>	<b>-4.10</b>	<b>1.47E-06</b>	<b>-3.11</b>	<b>2.88E-07</b>	<b>0.990</b>	<b>1.32</b>	<b>0.029</b>
		<b>Fgfr1</b>	<b>-2.42</b>	<b>1.90E-05</b>	<b>-4.04</b>	<b>2.04E-06</b>	<b>-1.621</b>	<b>-1.67</b>	<b>0.003</b>
	Cell adhesion	<b>Acan</b>	<b>-11.72</b>	<b>7.52E-09</b>	<b>-4.80</b>	<b>8.52E-06</b>	<b>6.923</b>	<b>2.44</b>	<b>0.011</b>
		<b>Cd4</b>	<b>-1.53</b>	<b>0.043</b>	<b>-1.77</b>	<b>0.045</b>	<b>-0.247</b>	-1.16	0.468
		<b>Cd44</b>	<b>5.28</b>	<b>1.12E-04</b>	1.63	0.231	<b>-3.650</b>	<b>-3.24</b>	<b>0.002</b>
		<b>Cdh1</b>	<b>-2.87</b>	<b>2.31E-05</b>	<b>-7.85</b>	<b>3.12E-07</b>	<b>-4.974</b>	<b>-2.73</b>	<b>0.001</b>
		<b>Cdh2</b>	<b>1.36</b>	<b>0.003</b>	1.44	0.089	<b>0.078</b>	1.06	0.584
		<b>Ctnna1</b>	<b>-2.51</b>	<b>2.24E-05</b>	<b>-3.63</b>	<b>6.44E-06</b>	<b>-1.124</b>	<b>-1.45</b>	<b>0.013</b>
		<b>Ncam1</b>	<b>3.01</b>	<b>0.007</b>	2.03	0.103	<b>-0.975</b>	-1.48	0.245
	Cell-cell comms	<b>Vcan</b>	<b>12.47</b>	<b>0.001</b>	<b>7.99</b>	<b>0.023</b>	<b>-4.482</b>	-1.56	0.217
		<b>Dll1</b>	-1.21	0.349	1.38	0.114	<b>2.596</b>	<b>1.68</b>	<b>0.041</b>
		<b>Gja1</b>	<b>-2.43</b>	<b>2.39E-05</b>	<b>-3.22</b>	<b>4.16E-05</b>	<b>-0.782</b>	-1.32	0.102
		<b>Gjb1</b>	<b>-2.37</b>	<b>0.002</b>	<b>-65.49</b>	<b>4.69E-09</b>	<b>-63.119</b>	<b>-27.64</b>	<b>0.002</b>
	Chromosome regulators	<b>Hdac1</b>	<b>-8.04</b>	<b>1.25E-06</b>	<b>-7.08</b>	<b>1.03E-07</b>	<b>0.966</b>	1.14	0.734
		<b>Hdac2</b>	<b>-2.20</b>	<b>9.23E-06</b>	<b>-1.82</b>	<b>0.001</b>	<b>0.379</b>	1.21	0.120
		<b>Kat2a</b>	<b>-5.62</b>	<b>7.56E-07</b>	<b>-6.63</b>	<b>1.39E-07</b>	<b>-1.011</b>	-1.18	0.314
		<b>Myst1</b>	<b>-3.74</b>	<b>2.91E-05</b>	<b>-4.03</b>	<b>2.82E-05</b>	<b>-0.291</b>	-1.08	0.129
		<b>Tert</b>	<b>-3.15</b>	<b>1.52E-04</b>	<b>-2.81</b>	<b>2.95E-04</b>	<b>0.342</b>	1.12	0.374
	GF and cytokines	<b>Bmp1</b>	1.28	<b>0.019</b>	-1.66	0.071	<b>-2.942</b>	<b>-2.13</b>	<b>0.005</b>
		<b>Bmp2</b>	7.73	<b>0.037</b>	2.70	<b>0.004</b>	<b>-5.031</b>	<b>-2.87</b>	<b>0.043</b>
		<b>Bmp3</b>	7.38	<b>0.039</b>	5.33	<b>0.002</b>	<b>-2.053</b>	-1.39	0.217
		<b>Cxcl12</b>	6.77	<b>0.014</b>	2.47	0.140	<b>-4.301</b>	-2.74	0.055
		<b>Gdf3</b>	<b>-35.19</b>	<b>2.47E-08</b>	<b>-18.90</b>	<b>2.09E-06</b>	<b>16.298</b>	1.86	0.290
		<b>Igf1</b>	<b>30.25</b>	<b>0.004</b>	<b>4.30</b>	<b>0.039</b>	<b>-25.956</b>	<b>-7.04</b>	<b>0.002</b>
		<b>Jag1</b>	-1.33	0.050	<b>-1.75</b>	<b>0.002</b>	<b>-0.418</b>	-1.31	0.106
		<b>Dhh</b>	<b>-2.84</b>	<b>0.013</b>	<b>-4.71</b>	<b>0.004</b>	<b>-1.872</b>	-1.66	0.070
Regulation cell division	<b>Notch1</b>	<b>-2.38</b>	<b>0.001</b>	<b>-2.46</b>	<b>4.65E-06</b>	<b>-0.077</b>	-1.03	0.715	
	<b>Numb</b>	-1.04	0.879	<b>-2.59</b>	<b>6.76E-05</b>	<b>-1.546</b>	<b>-2.48</b>	<b>0.002</b>	
	<b>Hspa9</b>	<b>-9.89</b>	<b>3.77E-06</b>	<b>-13.22</b>	<b>2.61E-06</b>	<b>-3.321</b>	-1.34	0.160	
Self-renewal	<b>Myst2</b>	<b>-3.88</b>	<b>3.69E-08</b>	<b>-5.60</b>	<b>1.22E-07</b>	<b>-1.713</b>	<b>-1.44</b>	<b>0.007</b>	
	<b>Neurog2</b>	28.34	0.091	<b>39.30</b>	<b>0.006</b>	<b>10.961</b>	1.39	0.438	
	<b>Sox1</b>	<b>-22.94</b>	<b>0.034</b>	-4.85	0.076	<b>18.090</b>	4.73	0.096	
	<b>Sox2</b>	<b>-15.95</b>	<b>7.56E-08</b>	<b>-6.67</b>	<b>1.18E-05</b>	<b>9.278</b>	2.39	0.063	
	Terminal differentiation markers								
Ectoderm	Epidermal	<b>Krt1</b>	<b>10.91</b>	<b>0.031</b>	1.90	0.092	<b>-9.015</b>	<b>-5.75</b>	<b>0.019</b>
		<b>Krt10</b>	<b>2.01</b>	<b>0.010</b>	1.48	0.168	<b>-0.537</b>	-1.36	0.208
		<b>Krt14</b>	53.67	0.070	1.82	0.232	<b>-51.852</b>	<b>-29.55</b>	<b>0.038</b>
		<b>Pmel</b>	<b>-2.39</b>	<b>2.50E-04</b>	<b>-1.55</b>	<b>0.00E+00</b>	<b>0.842</b>	<b>1.54</b>	<b>0.010</b>
		<b>Tyr</b>	6.34	0.085	44.12	0.059	<b>37.784</b>	<b>6.96</b>	<b>0.049</b>
	Neural	<b>Galc</b>	<b>2.97</b>	<b>2.24E-04</b>	<b>2.55</b>	<b>0.026</b>	<b>-0.413</b>	-1.16	0.514
		<b>Isl1</b>	<b>34.46</b>	<b>0.002</b>	24.94	0.050	<b>-9.520</b>	-1.38	0.891
		<b>Mbp</b>	<b>6.41</b>	<b>0.013</b>	2.77	<b>0.003</b>	<b>-3.639</b>	<b>-2.32</b>	<b>0.025</b>
		<b>Mtap2</b>	1.85	0.194	3.98	<b>0.021</b>	<b>2.123</b>	2.15	0.125
		<b>Nefh</b>	<b>-7.75</b>	<b>0.001</b>	<b>-2.50</b>	<b>0.011</b>	<b>5.250</b>	<b>3.10</b>	<b>0.015</b>
		<b>Slc17a6</b>	16.85	0.185	<b>44.69</b>	<b>0.032</b>	<b>27.844</b>	2.65	0.478
		<b>Slc17a7</b>	<b>-2.03</b>	<b>0.008</b>	<b>-2.67</b>	<b>0.002</b>	<b>-0.643</b>	-1.32	0.189
	Retina	<b>Tubb3</b>	<b>-4.01</b>	<b>2.59E-04</b>	1.18	0.236	<b>5.192</b>	<b>4.74</b>	<b>0.001</b>
		<b>Pde6b</b>	3.08	<b>2.19E-04</b>	2.85	<b>4.84E-04</b>	<b>-0.231</b>	-1.08	0.400
		<b>Pou4f2</b>	<b>-15.77</b>	<b>2.24E-04</b>	<b>-2.62</b>	<b>0.003</b>	<b>13.150</b>	<b>6.01</b>	<b>0.001</b>
		<b>Rlbp1</b>	<b>-2.88</b>	<b>4.31E-05</b>	<b>-2.30</b>	<b>0.008</b>	<b>0.581</b>	1.25	0.310

(continued)

TABLE 1. (CONTINUED)

Category	Symbol	mESC -> GC		mESC -> FLT		Changes in fold change of GC vs. FLT	GC -> FLT		
		Fold D	P value	Fold D	P value		Fold D	P value	
Mesoderm	Adipose	<b>Pparg</b>	<b>87.81</b>	<b>0.018</b>	12.34	0.069	-75.473	-7.12	<b>0.015</b>
	Bone	<b>Bglap2</b>	<b>5.64</b>	<b>0.013</b>	2.39	0.124	-3.250	-2.36	<b>0.046</b>
		<b>Calcr</b>	1.82	0.064	<b>13.22</b>	<b>0.008</b>	<b>11.402</b>	7.27	<b>0.004</b>
		<b>Col2a1</b>	<b>21.35</b>	<b>0.028</b>	<b>19.96</b>	<b>0.018</b>	-1.386	-1.07	0.837
	Bone marrow	<b>Ctsk</b>	<b>10.22</b>	<b>0.002</b>	4.28	0.111	-5.945	-2.39	<b>0.044</b>
		<b>Ccr5</b>	<b>99.34</b>	<b>0.020</b>	1.27	0.584	-98.064	-77.98	<b>0.007</b>
		<b>Cd3e</b>	-6.12	<b>0.001</b>	-1.87	0.093	4.252	3.28	<b>0.040</b>
		<b>Cd79a</b>	-1.50	<b>0.049</b>	-1.59	<b>0.012</b>	-0.091	-1.06	0.723
		<b>Cxcr4</b>	7.45	<b>0.009</b>	<b>10.71</b>	<b>0.007</b>	3.256	1.44	0.193
		<b>Emr1</b>	<b>14032.47</b>	<b>0.004</b>	206.73	0.231	-13825.75	-67.88	<b>0.001</b>
		<b>Itgam</b>	<b>44.03</b>	<b>0.007</b>	2.86	0.149	-41.167	-15.39	<b>0.003</b>
		<b>Ptcr</b>	1.76	<b>0.029</b>	1.93	0.305	0.174	1.10	0.560
	Cardiovascular system	<b>Dll4</b>	<b>73.47</b>	<b>0.001</b>	<b>46.41</b>	<b>0.018</b>	-27.056	-1.58	0.190
		<b>Efnb2</b>	3.55	<b>9.10E-05</b>	4.28	<b>0.023</b>	0.731	1.21	0.336
		<b>Myh6</b>	<b>15902.77</b>	<b>1.65E-04</b>	3284.04	0.056	-12618.731	-4.84	<b>0.014</b>
		<b>Myh7</b>	<b>65.37</b>	<b>0.002</b>	17.24	0.109	-48.128	-3.79	<b>0.049</b>
		<b>Nppa</b>	4.11	<b>0.002</b>	2.71	<b>0.002</b>	-1.407	-1.52	<b>0.034</b>
		<b>Nr2f2</b>	<b>1093.35</b>	<b>0.010</b>	871.36	0.065	-221.988	-1.25	0.900
		<b>Nrp1</b>	<b>122.98</b>	<b>8.61E-05</b>	<b>45.49</b>	<b>0.048</b>	-77.493	-2.70	<b>0.017</b>
		<b>Nrp2</b>	2.15	<b>1.57E-04</b>	1.28	0.352	-0.865	-1.67	0.076
	Cartilage	<b>Acan</b>	-2.63	<b>1.90E-05</b>	-1.26	0.294	1.369	2.08	<b>0.017</b>
		<b>Col10a1</b>	-4.46	0.210	3.06	<b>0.003</b>	7.511	13.61	0.470
		<b>Comp</b>	4.05	<b>0.013</b>	1.30	0.286	-2.749	-3.12	<b>0.009</b>
	Kidney	<b>Aqp1</b>	<b>239.71</b>	<b>0.002</b>	23.74	0.077	-215.964	-10.10	<b>0.001</b>
		<b>Aqp2</b>	-1.45	0.371	4.07	<b>0.048</b>	5.520	5.91	<b>0.012</b>
		<b>Cyp27b1</b>	-1.02	0.887	-2.43	<b>0.007</b>	-1.409	-2.39	<b>0.003</b>
		<b>Miox</b>	-5.12	<b>1.55E-04</b>	-2.57	0.373	2.542	1.99	0.262
		<b>Nphs2</b>	3.94	<b>2.85E-04</b>	4.59	0.135	0.659	1.17	0.503
	Lymphatic	<b>Lyve1</b>	<b>3601.94</b>	<b>0.018</b>	282.89	0.148	-3319.046	-12.73	<b>0.012</b>
		<b>Prox1</b>	<b>18.02</b>	<b>0.001</b>	<b>14.74</b>	<b>0.008</b>	-3.283	-1.22	0.494
	Muscle	<b>Cav3</b>	<b>71.64</b>	<b>0.018</b>	9.65	0.154	-61.996	-7.43	<b>0.020</b>
		<b>Smtn</b>	3.10	<b>0.001</b>	1.47	<b>0.049</b>	-1.631	-2.11	<b>0.002</b>
<b>Tagln</b>		3.66	<b>0.017</b>	-1.26	0.971	-4.915	-4.60	<b>0.009</b>	
Endoderm	Liver	<b>Itgb4</b>	6.47	<b>0.010</b>	1.75	0.052	-4.716	-3.69	<b>0.007</b>
		<b>Krt19</b>	4.77	<b>1.53E-05</b>	2.18	<b>0.047</b>	-2.584	-2.18	<b>0.002</b>
	Lung	<b>Sftpc</b>	<b>20.10</b>	<b>0.002</b>	27.63	0.164	7.536	1.37	0.414
		<b>Sftpd</b>	6.18	<b>0.006</b>	3.11	<b>0.020</b>	-3.069	-1.99	<b>0.030</b>
	Pancreas	<b>Ghrl</b>	3.21	<b>3.75E-05</b>	2.25	<b>0.002</b>	-0.955	-1.42	<b>0.006</b>
		<b>Mafa</b>	-7.83	<b>5.88E-05</b>	-9.28	<b>3.37E-05</b>	-1.445	-1.18	0.367
		<b>Mafb</b>	<b>26.96</b>	<b>4.39E-06</b>	8.36	<b>0.019</b>	-18.604	-3.23	<b>2.46E-04</b>
		<b>Pou3f4</b>	1.36	0.233	<b>17.03</b>	<b>0.044</b>	15.674	12.52	0.692
		<b>Slc2a2</b>	<b>215.52</b>	<b>0.001</b>	13.60	0.089	-201.920	-15.85	<b>4.22E-04</b>
		<b>Sst</b>	<b>98.51</b>	<b>0.044</b>	429.62	0.105	331.107	4.36	0.105
p53 signaling									
p53 and cell cycle	Cell cycle regulation	<b>Apc</b>	-3.01	<b>2.02E-05</b>	-2.95	<b>2.18E-05</b>	0.066	1.02	0.607
		<b>Axin1</b>	-3.25	<b>6.26E-06</b>	-4.31	<b>2.76E-06</b>	-1.062	-1.33	<b>0.032</b>
		<b>Ccna2</b>	-3.25	<b>2.25E-06</b>	-2.50	<b>5.31E-05</b>	0.750	1.30	<b>0.038</b>
		<b>Ccnb2</b>	-1.39	0.166	1.03	0.734	2.415	1.42	0.104
		<b>Ccnd1</b>	-4.29	<b>8.01E-06</b>	-3.69	<b>5.76E-06</b>	0.606	1.16	0.467
		<b>Ccnd2</b>	7.41	<b>0.002</b>	4.64	<b>0.033</b>	-2.761	-1.59	0.168
		<b>Ccne1</b>	-12.07	<b>1.73E-10</b>	-7.80	<b>3.68E-07</b>	4.269	1.55	0.061
		<b>Ccne2</b>	1.57	<b>2.60E-05</b>	1.39	0.071	-0.179	-1.13	0.337
		<b>Ccng1</b>	2.80	<b>0.003</b>	2.90	<b>0.005</b>	0.104	1.04	0.771
		<b>Ccng2</b>	3.24	<b>2.44E-04</b>	1.95	<b>0.018</b>	-1.291	-1.66	<b>0.007</b>
		<b>Ccnh</b>	-1.20	<b>0.042</b>	-1.06	0.502	0.143	1.14	0.163

(continued)

TABLE 1. (CONTINUED)

Category	Symbol	mESC -> GC		mESC -> FLT		Changes in fold change of GC vs. FLT	GC -> FLT		
		Fold D	P value	Fold D	P value		Fold D	P value	
	Cdc25a	1.01	0.874	-1.05	0.689	-2.061	-1.06	0.652	
	Cdc25c	-1.21	0.267	1.06	0.397	2.274	1.29	0.105	
	<b>Cdc42</b>	<b>-1.53</b>	<b>0.001</b>	<b>-2.50</b>	<b>3.61E-05</b>	<b>-0.964</b>	<b>-1.63</b>	<b>0.003</b>	
	<b>Cdk1</b>	<b>-2.79</b>	<b>8.32E-07</b>	<b>-2.89</b>	<b>0.000</b>	<b>-0.095</b>	-1.03	0.521	
	Cdk4	-1.17	0.579	1.27	0.316	2.443	1.49	0.143	
	<b>Cdkn2a</b>	<b>2.98</b>	<b>0.008</b>	<b>1.43</b>	<b>0.044</b>	<b>-1.545</b>	<b>-2.08</b>	<b>0.010</b>	
	E2f3	1.06	0.702	1.13	0.594	0.072	1.07	0.768	
	<b>Ep300</b>	<b>-3.05</b>	<b>1.31E-06</b>	<b>-4.20</b>	<b>4.54E-06</b>	<b>-1.148</b>	-1.38	0.054	
	<b>Fgf1</b>	<b>-1.11</b>	<b>0.509</b>	<b>-2.72</b>	<b>0.003</b>	<b>-1.604</b>	<b>-2.44</b>	<b>0.007</b>	
	<b>Fgf2</b>	<b>4.96</b>	<b>0.026</b>	-1.09	0.917	<b>-6.051</b>	<b>-5.43</b>	<b>0.010</b>	
	<b>Fgf4</b>	<b>-21.49</b>	<b>5.33E-07</b>	<b>-9.10</b>	<b>4.56E-05</b>	<b>12.385</b>	2.36	0.169	
	Kras	-1.10	0.768	-1.00	0.895	0.098	1.10	0.711	
	<b>Myc</b>	<b>-5.73</b>	<b>0.001</b>	<b>-7.32</b>	<b>3.17E-04</b>	<b>-1.592</b>	-1.28	0.218	
	<b>Notch2</b>	<b>-1.89</b>	<b>2.72E-04</b>	<b>-2.85</b>	<b>2.77E-07</b>	<b>-0.959</b>	<b>-1.51</b>	<b>0.005</b>	
	<b>Numb</b>	<b>3.16</b>	<b>0.001</b>	<b>1.61</b>	<b>0.029</b>	<b>-1.552</b>	<b>-1.96</b>	<b>0.002</b>	
	<b>Pard6a</b>	<b>-4.51</b>	<b>2.58E-06</b>	<b>-5.85</b>	<b>8.41E-07</b>	<b>-1.342</b>	-1.30	0.110	
	<b>Ppm1d</b>	<b>2.07</b>	<b>0.004</b>	<b>1.68</b>	<b>0.001</b>	<b>-0.391</b>	-1.24	0.076	
	<b>Prc1</b>	<b>-1.33</b>	<b>0.003</b>	<b>-1.32</b>	<b>0.023</b>	<b>0.005</b>	1.01	0.898	
	<b>Rb1</b>	<b>-1.93</b>	<b>0.005</b>	<b>-2.09</b>	<b>0.005</b>	<b>-0.158</b>	-1.08	0.552	
	<b>Rprm</b>	<b>6.10</b>	<b>0.007</b>	<b>7.05</b>	<b>0.016</b>	<b>0.945</b>	1.16	0.501	
	<b>Sesn2</b>	<b>-1.52</b>	<b>0.029</b>	1.10	0.527	<b>2.616</b>	<b>1.67</b>	<b>0.041</b>	
p53 activation and regulation	Atm	1.05	0.688	1.05	0.628	0.003	-1.00	0.923	
	Atr	1.24	0.267	1.25	0.173	0.006	1.00	0.965	
	<b>Brca1</b>	<b>-1.51</b>	<b>0.046</b>	-1.18	0.282	<b>0.331</b>	1.28	0.125	
	<b>Brca2</b>	<b>-1.67</b>	<b>0.011</b>	-1.04	0.752	<b>0.632</b>	<b>1.61</b>	<b>0.011</b>	
	<b>Cdkn1a</b>	<b>7.22</b>	<b>1.41E-04</b>	<b>5.61</b>	<b>0.005</b>	<b>-1.611</b>	-1.29	0.205	
	<b>Chek1</b>	<b>-2.07</b>	<b>4.89E-04</b>	<b>-1.68</b>	<b>0.001</b>	<b>0.391</b>	1.23	0.113	
	<b>Chek2</b>	<b>-1.89</b>	<b>0.026</b>	-1.37	0.281	<b>0.524</b>	1.38	0.291	
	<b>Foxo3</b>	<b>3.63</b>	<b>9.00E-06</b>	<b>2.34</b>	<b>3.26E-04</b>	<b>-1.292</b>	<b>-1.55</b>	<b>2.63E-04</b>	
	<b>Mdm2</b>	<b>1.87</b>	<b>0.021</b>	1.29	0.216	<b>-0.576</b>	-1.45	0.091	
	<b>Msh2</b>	<b>-1.83</b>	<b>0.002</b>	-1.46	0.059	<b>0.375</b>	1.26	0.235	
	<b>Pmaip1</b>	<b>-2.14</b>	<b>0.018</b>	-1.26	0.256	<b>0.882</b>	1.70	0.111	
	<b>Sirt1</b>	<b>-2.87</b>	<b>0.004</b>	-1.61	0.226	<b>1.264</b>	1.79	0.170	
	<b>Trp53bp2</b>	<b>1.89</b>	<b>0.010</b>	1.74	0.056	<b>-0.153</b>	-1.09	0.728	
	Trp63	236.98	0.054	119.58	0.141	<b>-117.396</b>	-1.98	0.390	
	Trp73	-1.87	0.152	1.01	0.812	<b>2.878</b>	1.88	0.182	
Target	Angiogenesis	<b>Il6</b>	<b>34.83</b>	<b>0.021</b>	7.03	0.224	<b>-27.795</b>	-4.95	0.051
		Pten	1.34	0.061	1.35	<b>0.038</b>	<b>0.005</b>	1.00	0.992
	Apoptosis	<b>Apaf1</b>	<b>1.75</b>	<b>1.13E-04</b>	<b>1.32</b>	<b>0.042</b>	<b>-0.432</b>	<b>-1.33</b>	<b>0.006</b>
		Bax	1.11	0.297	1.03	0.597	<b>-0.082</b>	-1.08	0.342
		<b>Btg2</b>	<b>4.86</b>	<b>0.005</b>	<b>3.15</b>	<b>0.012</b>	<b>-1.707</b>	-1.54	0.092
		<b>Casp9</b>	<b>1.91</b>	<b>0.003</b>	1.56	0.125	<b>-0.349</b>	-1.22	0.390
		<b>Esr1</b>	<b>56.92</b>	<b>0.025</b>	21.67	0.161	<b>-35.250</b>	-2.63	0.222
		<b>Pmaip1</b>	<b>-2.14</b>	<b>0.018</b>	-1.26	0.256	<b>0.882</b>	1.70	0.111
		<b>Prkca</b>	<b>17.59</b>	<b>0.001</b>	4.60	0.101	<b>-12.994</b>	<b>-3.83</b>	<b>0.004</b>
		<b>Sfn</b>	<b>-3.09</b>	<b>1.03E-04</b>	<b>-4.53</b>	<b>1.05E-05</b>	<b>-1.439</b>	<b>-1.47</b>	<b>0.043</b>
		<b>Tnf</b>	<b>4.57</b>	<b>0.003</b>	-1.02	0.650	<b>-5.586</b>	<b>-4.64</b>	<b>0.046</b>
		<b>Tnfrsf10b</b>	<b>1.83</b>	<b>0.016</b>	1.36	0.167	<b>-0.468</b>	-1.34	0.149
		<b>Trp53</b>	<b>-1.81</b>	<b>0.001</b>	-1.32	0.137	<b>0.489</b>	1.37	0.105
		Trp73	-1.87	0.152	1.01	0.812	<b>2.878</b>	1.88	0.182
		Zmat3	1.13	0.447	1.34	0.266	<b>0.208</b>	1.18	0.436
	DNA repair	<b>Brca1</b>	<b>-1.51</b>	<b>0.046</b>	-1.18	0.282	<b>0.331</b>	1.28	0.125
		<b>Btg2</b>	<b>4.86</b>	<b>0.005</b>	<b>3.15</b>	<b>0.012</b>	<b>-1.707</b>	-1.54	0.092
		<b>Gadd45a</b>	<b>-2.54</b>	<b>2.00E-06</b>	<b>-3.76</b>	<b>5.55E-07</b>	<b>-1.216</b>	<b>-1.48</b>	<b>0.003</b>
		<b>Pcna</b>	<b>-1.74</b>	<b>0.016</b>	-1.18	0.082	<b>0.563</b>	1.48	0.057
		<b>Pttg1</b>	<b>2.66</b>	<b>0.001</b>	1.67	0.148	<b>-0.989</b>	-1.59	0.085

(continued)

TABLE 1. (CONTINUED)

Category	Symbol	mESC → GC		mESC → FLT		Changes in fold change of GC vs. FLT	GC → FLT		
		Fold D	P value	Fold D	P value		Fold D	P value	
Downstream	Apoptosis	<b>Apaf1</b>	<b><i>1.75</i></b>	<b><i>1.13E-04</i></b>	<i>1.32</i>	<b><i>0.042</i></b>	<b><i>-0.432</i></b>	<i>-1.33</i>	<b><i>0.006</i></b>
		Bag1	<i>-1.01</i>	<i>0.982</i>	<i>-1.07</i>	<i>0.786</i>	<b><i>-0.058</i></b>	<i>-1.05</i>	<i>0.792</i>
		<b>Bcl2</b>	<b><i>7.57</i></b>	<b><i>0.005</i></b>	<i>4.73</i>	<i>0.085</i>	<b><i>-2.839</i></b>	<i>-1.60</i>	<i>0.297</i>
		<b>Bid</b>	<b><i>-1.49</i></b>	<b><i>0.037</i></b>	<i>-1.39</i>	<i>0.112</i>	<b><i>0.104</i></b>	<i>1.08</i>	<i>0.669</i>
		Birc5	<i>-1.13</i>	<i>0.164</i>	<i>1.07</i>	<i>0.254</i>	<b><i>2.197</i></b>	<b><i>1.21</i></b>	<b><i>0.046</i></b>
		<b>Bnip3</b>	<b><i>1.57</i></b>	<b><i>0.011</i></b>	<i>1.12</i>	<i>0.127</i>	<b><i>-0.453</i></b>	<i>-1.40</i>	<b><i>0.011</i></b>
		Casp2	<i>1.55</i>	<i>0.084</i>	<i>1.20</i>	<i>0.428</i>	<b><i>-0.354</i></b>	<i>-1.30</i>	<i>0.342</i>
		<b>Casp9</b>	<b><i>1.91</i></b>	<b><i>0.003</i></b>	<i>1.56</i>	<i>0.125</i>	<b><i>-0.349</i></b>	<i>-1.22</i>	<i>0.390</i>
		<b>Cradd</b>	<b><i>-1.59</i></b>	<b><i>0.004</i></b>	<i>1.02</i>	<i>0.774</i>	<b><i>2.607</i></b>	<b><i>1.62</i></b>	<b><i>0.003</i></b>
		<b>Cul9</b>	<b><i>5.51</i></b>	<b><i>0.002</i></b>	<i>5.49</i>	<i>0.060</i>	<b><i>-0.025</i></b>	<i>-1.00</i>	<i>0.729</i>
		Dapk1	<i>2.30</i>	<i>0.062</i>	<b><i>2.93</i></b>	<b><i>0.009</i></b>	<b><i>0.629</i></b>	<i>1.27</i>	<i>0.416</i>
		E2f1	<i>-1.36</i>	<i>0.422</i>	<i>-1.29</i>	<i>0.340</i>	<b><i>0.075</i></b>	<i>1.06</i>	<i>0.971</i>
		E2f3	<i>1.06</i>	<i>0.702</i>	<i>1.13</i>	<i>0.594</i>	<b><i>0.072</i></b>	<i>1.07</i>	<i>0.768</i>
		<b>Fadd</b>	<b><i>3.56</i></b>	<b><i>0.001</i></b>	<i>3.61</i>	<i>0.170</i>	<b><i>0.047</i></b>	<i>1.01</i>	<i>0.662</i>
		Fasl	<i>5.83</i>	<i>0.055</i>	<i>6.26</i>	<i>0.207</i>	<b><i>0.425</i></b>	<i>1.07</i>	<i>0.688</i>
		<b>Mcl1</b>	<b><i>-1.66</i></b>	<b><i>0.029</i></b>	<b><i>-1.82</i></b>	<b><i>0.009</i></b>	<b><i>-0.158</i></b>	<i>-1.09</i>	<i>0.647</i>
	<b>Nf1</b>	<b><i>4.59</i></b>	<b><i>0.004</i></b>	<i>3.40</i>	<i>0.080</i>	<b><i>-1.193</i></b>	<i>-1.35</i>	<i>0.472</i>	
	<b>Nfkb1</b>	<b><i>1.54</i></b>	<b><i>0.036</i></b>	<i>1.15</i>	<i>0.355</i>	<b><i>-0.392</i></b>	<i>-1.34</i>	<i>0.119</i>	
	<b>Rela</b>	<b><i>2.43</i></b>	<b><i>0.001</i></b>	<i>1.79</i>	<i>0.077</i>	<b><i>-0.637</i></b>	<i>-1.36</i>	<i>0.169</i>	
	Traf1	<i>-1.03</i>	<i>0.979</i>	<i>-1.24</i>	<i>0.903</i>	<b><i>-0.209</i></b>	<i>-1.20</i>	<i>0.881</i>	
	<b>Wt1</b>	<b><i>-1.55</i></b>	<b><i>0.003</i></b>	<i>-1.04</i>	<i>0.821</i>	<b><i>0.512</i></b>	<i>1.49</i>	<i>0.240</i>	
	DNA repair	<b>Apex1</b>	<b><i>-1.84</i></b>	<b><i>0.004</i></b>	<i>-1.39</i>	<b><i>0.002</i></b>	<b><i>0.449</i></b>	<i>1.32</i>	<i>0.096</i>
		<b>Brca2</b>	<b><i>-1.67</i></b>	<b><i>0.011</i></b>	<i>-1.04</i>	<i>0.752</i>	<b><i>0.632</i></b>	<b><i>1.61</i></b>	<b><i>0.011</i></b>
		Ercc1	<i>1.15</i>	<i>0.077</i>	<i>1.10</i>	<i>0.338</i>	<b><i>-0.053</i></b>	<i>-1.05</i>	<i>0.634</i>
		Lig4	<i>-1.05</i>	<i>0.970</i>	<i>1.17</i>	<i>0.454</i>	<b><i>2.216</i></b>	<i>1.23</i>	<i>0.450</i>
		<b>Xrcc4</b>	<b><i>1.42</i></b>	<b><i>0.010</i></b>	<i>1.18</i>	<i>0.103</i>	<b><i>-0.238</i></b>	<i>-1.21</i>	<i>0.082</i>
		<b>Xrcc5</b>	<b><i>-2.08</i></b>	<b><i>0.001</i></b>	<b><i>-1.54</i></b>	<b><i>0.010</i></b>	<b><i>0.541</i></b>	<i>1.35</i>	<i>0.064</i>
	TF	<b>Egr1</b>	<b><i>3.78</i></b>	<b><i>0.027</i></b>	<i>1.31</i>	<i>0.467</i>	<b><i>-2.466</i></b>	<b><i>-2.87</i></b>	<b><i>0.049</i></b>
		<b>Hif1a</b>	<b><i>1.64</i></b>	<b><i>0.026</i></b>	<i>1.33</i>	<i>0.104</i>	<b><i>-0.309</i></b>	<i>-1.24</i>	<i>0.217</i>
		<b>Jun</b>	<b><i>4.33</i></b>	<b><i>0.002</i></b>	<i>2.12</i>	<i>0.076</i>	<b><i>-2.210</i></b>	<b><i>-2.04</i></b>	<b><i>0.019</i></b>
		Myod1	<i>16.49</i>	<i>0.167</i>	<i>64.58</i>	<i>0.122</i>	<b><i>48.086</i></b>	<i>3.92</i>	<i>0.222</i>
		<b>Nfkb1</b>	<b><i>1.54</i></b>	<b><i>0.036</i></b>	<i>1.15</i>	<i>0.355</i>	<b><i>-0.392</i></b>	<i>-1.34</i>	<i>0.119</i>
<b>Rela</b>		<b><i>2.43</i></b>	<b><i>0.001</i></b>	<i>1.79</i>	<i>0.077</i>	<b><i>-0.637</i></b>	<i>-1.36</i>	<i>0.169</i>	
<b>Stat1</b>		<b><i>12.52</i></b>	<b><i>0.002</i></b>	<b><i>4.13</i></b>	<b><i>0.017</i></b>	<b><i>-8.389</i></b>	<b><i>-3.03</i></b>	<b><i>0.005</i></b>	

*Bold italics* indicates upregulation, *bold* indicates downregulation and *italics* indicates no significant biological change of test samples compared to controls in each respective column (GC vs. mESCs, FLT vs. mESCs, FLT vs. GC). Highlighting indicates net downregulation (*dark gray*), upregulation (*gray*) or no change (*light gray*) in fold change of  $\mu$ g and 1xg controls compared to undifferentiated mESCs. *Bold underlined* indicates significant change ( $P < 0.05$ ).

1xg, Earth's gravity; mESC, mouse embryonic stem cell; GC, ground control; FLT, spaceflight.

*Gene expression of terminal lineage differentiation markers.* To further investigate the effects of spaceflight on differentiation into multiple cell lineages, we conducted RT-qPCR analysis of terminal lineage differentiation markers from the three germ layers—mesoderm, endoderm, and ectoderm. We specifically investigated genes associated with terminal differentiation of adipose, bone, bone marrow, cardiovascular, cartilage, kidney, lymphatic, and muscle tissues. The adipose tissue marker PPAR $\gamma$  was downregulated in EBs differentiated in  $\mu$ g conditions compared with 1xg controls ( $-7.12$ ,  $P < 0.05$ ). COL2A1 showed similar levels of expression in 1xg controls and  $\mu$ g samples compared to undifferentiated mESCs (19.96 and 21.25-fold respectively,  $P < 0.05$ ), however, expression of CTSK and BGLAP were significantly decreased in  $\mu$ g samples ( $-2.93$  and  $-2.36$ -fold respectively,  $P < 0.05$ , Fig. 4D). CALCR was increased in EBs differenti-

ated in  $\mu$ g conditions compared with 1xg controls (7.27,  $P < 0.01$ , Fig. 4D). Importantly, markers for immune cells including EMR1, CCR5, and ITGAM were significantly downregulated in microgravity samples compared with 1xg controls ( $-67.88$ ,  $-77.98$ , and  $-15.39$ -fold respectively,  $P < 0.01$ , Fig. 4D, Table 1). We also found decreases in a number of cardiovascular differentiation markers. Specifically, cardiomyocyte markers (MYH6 and MYH7), arterial endothelium markers (NRP1), and lymphatic endothelial markers (LYVE1) were downregulated in EBs differentiated in  $\mu$ g compared with 1xg ( $-4.84$ ,  $-3.79$ ,  $-2.70$ , and  $-12.73$ -fold respectively,  $P < 0.05$ ). DLL4, exhibited significant increases in  $\mu$ g and 1xg samples compared with undifferentiated mESCs (73.47 and 46.41-fold respectively,  $P < 0.05$ ), however, the increase in expression for the  $\mu$ g samples was less than the increases in 1xg controls and compared with levels in

undifferentiated mESCs. The cartilage specific differentiation marker, COMP was also altered in  $\mu\text{g}$  samples compared to 1xg controls ( $-3.12$ ,  $P < 0.01$ ). COL10A1 exhibited increased expression in EBs differentiated in  $\mu\text{g}$  samples compared with undifferentiated mESCs (3.06-fold,  $P < 0.01$ ), however, no significant differences were found when compared to EBs differentiated at 1xg (Table 1). We also found decreased expression in kidney markers AQP1 and CYP27B1 ( $-10.1$  and  $-2.39$ -fold respectively,  $P < 0.01$ ). On the other hand, AQP2 had increased expression in  $\mu\text{g}$  samples compared with 1xg controls (5.91,  $P < 0.05$ , Fig. 4D). Investigation into terminal muscle lineage markers resulted in decreased expression of CAV3 ( $-7.4$ -fold,  $P < 0.05$ ), TAGLN ( $-4.6$ -fold,  $P < 0.05$ ), and SMTN ( $-2.1$ -fold,  $P < 0.05$ ) in EBs differentiated in  $\mu\text{g}$  compared with 1xg controls (Fig. 4D).

Significant alterations in differentiation of tissues from the ectoderm and endoderm germ layers also were observed in EBs differentiated in  $\mu\text{g}$  conditions (Figs. 4 and 6). Specifically, epidermal lineage markers including KRT1, 14, and 15, were downregulated ( $-5.75$ ,  $-29.55$ , and  $-24.9$ -fold,  $P < 0.05$ , Fig. 4E) while expression of PMEL, a protein expressed in pigment cells, was upregulated in  $\mu\text{g}$  differentiated EBs (1.5-fold,  $P < 0.01$ , Fig. 4E). The retinal ganglion cell marker, POU4F2 was increased in  $\mu\text{g}$ -differentiated EBs compared with 1xg controls (6.01-fold,  $P < 0.01$ , Table 1). Markers for neural tissue differentiation showed increased expression in  $\mu\text{g}$  samples compared with 1xg controls. Specifically, the expression of two markers for mature neurons, TUBB3 and NEFH, showed increased expression in  $\mu\text{g}$ -differentiated EBs compared with 1xg controls (4.74 and 3.10-fold change respectively,  $P < 0.05$ , Fig. 4E). Markers for cholangiocytes, found in the liver, were also downregulated in  $\mu\text{g}$  samples, including ITGB4 ( $-3.69$ ,  $P < 0.01$ ) and KRT19 ( $-2.18$ ,  $P < 0.01$ ), as were markers for pancreatic cells, including SLC2A2 ( $-15.85$ ,  $P < 0.01$ ), MAFB ( $-3.23$ ,  $P < 0.01$ ), and GHRL ( $-1.42$ ,  $P < 0.01$ ), as seen in Fig. 4F.

Collectively, these results indicate that the expression of lineage-specific markers during differentiation at 1xg, fail to appear normally in  $\mu\text{g}$ , suggesting that stem cells in EBs did not fully differentiate under mechanically unloaded conditions.

*Gene expression analysis of the cell cycle and p53 signaling pathway.* Genes associated with cell cycle regulation and the p53 signaling pathway were then investigated, to determine whether  $\mu\text{g}$  reduced cell proliferation and increased apoptosis or cell cycle arrest (Fig. 5). In control/1xg conditions, stem cells differentiated into EBs showed downregulation of cell cycle genes possibly associated with differentiation. Specifically, mESCs differentiated into EBs at 1xg, showed increased expression of CDKN1a (7.22-fold,  $P < 0.01$ ). Although EBs differentiated in  $\mu\text{g}$  showed similar cell cycle arrest increase trends, the level of expression of cell cycle genes in  $\mu\text{g}$  was lower than that of 1xg controls, indicating greater proliferation potential (Fig. 5). We found, however, no significant alterations in TRP53 in EBs differentiated in  $\mu\text{g}$  versus 1xg, suggesting that apoptosis was not significantly changed at the time of fixation (Table 1). Furthermore, we also found no significant alterations in radiation response genes ATM and ATR (Fig. 5, Table 1). Upregulation of some apoptosis-related genes was observed in EBs differentiated at 1xg relative to undifferentiated mESCs, including BCL2 (7.57-fold,  $P < 0.01$ ), CUL9 (5.51,  $P < 0.01$ ), FADD (3.56,  $P < 0.01$ ), RELA (2.43,  $P < 0.01$ ), and CASP9 (1.91,  $P < 0.01$ ,

Fig. 5). DAPK1, on the other hand, displayed increased expression in EBs differentiated in  $\mu\text{g}$  compared with undifferentiated mESCs (2.93,  $P < 0.01$ ). These, however, were not significantly changed between 1xg and  $\mu\text{g}$ , and therefore their elevation of expression may be due to normal levels of apoptosis occurring during differentiation. Some p53 target genes showed increased expression in EBs differentiated at 1xg but not in EBs differentiated in  $\mu\text{g}$  compared to undifferentiated mESCs, including ESR1, PRKC $\alpha$ , and TNF (56.92, 17.59, 4.86 respectively,  $P < 0.05$ , Fig. 5). Finally, several downstream transcription factors also showed downregulation in  $\mu\text{g}$  samples compared with 1xg controls, including STAT1, JUN, and EGR1 ( $-3.03$ ,  $-2.04$ , and  $-2.87$ -fold respectively,  $P < 0.05$ , Fig. 5).

## Discussion

In this study we investigated in vitro differentiation of mESC cultures in  $\mu\text{g}$ , to quantify the role and importance of gravity-generated forces on earth in promoting stem cell-based tissue regenerative health. Spaceflight in  $\mu\text{g}$  is known to cause tissue degeneration in mammals via complex mechanisms that include active tissue degradation, but also, we hypothesize, by the arrest of stem cell-based tissue regeneration. Here, we focused on the mechanism of regenerative arrest due to mechanical unloading. We show that exposure to microgravity during spaceflight preserved progenitor stemness and inhibited the expression of terminal differentiation markers for tissues derived from all three primary germ layers.

Previous studies of ESCs using experimental models that simulate microgravity, such as RPM and RWV, have shown varied outcomes including decreased cell numbers associated with increased apoptosis, altered adhesion properties, and differentiation [10]. In contrast, following 15 days differentiation in actual  $\mu\text{g}$ , EBs had similar viability levels to those of 1xg controls, and similar matrix adhesion to fibronectin and collagen. EBs differentiated in  $\mu\text{g}$  appeared to consume slightly less glucose than those differentiated at 1xg, suggesting reduced cell number, mass, or reduced metabolic rate.

To further determine the effects of  $\mu\text{g}$  unloading on cell proliferation and apoptosis in EBs, genes associated with the cell cycle and the p53-signaling pathway were investigated. We found no alterations in the expression of majority of apoptosis-related genes, including p53, p53-regulating genes, and genes involved in p53 activation, suggesting unaltered levels of apoptosis. Similar upregulation of expression of some apoptosis-related genes was observed in both  $\mu\text{g}$  samples and 1xg controls relative to undifferentiated mESCs, and may be due to normal apoptosis during differentiation, such as occurs during digit development. Apoptosis may also occur inside EBs as they enlarge and the center of cell masses becomes anoxic and nutrient deprived due to lack of vascularization [21], or in cells that fail to adhere to EB masses. Because only initial undifferentiated mESCs and terminal samples of differentiation cultures were collected, it is formally possible that differential apoptosis may have occurred initially, resulting in decreases in cell number and therefore decreased glucose consumption. In fact,  $\mu\text{g}$  altered the expression of cyclins that control cell cycle progression (eg, CCNA2, CCND1, and CCNG2), suggesting a decrease in

proliferation. Although no alterations were seen in CDKs, increased expression of CDKN1a/p21 in both  $\mu\text{g}$ - and 1xg-differentiated EBs was observed, however, expression of CDKN1a/p21 in  $\mu\text{g}$  samples was significantly less than that of 1xg controls. CDKN1a/p21 upregulation can occur in arrest of cell cycle for differentiation, in response to cell irradiation resulting in DNA damage, in response to oxidative damage, or in senescent cells [22–27]. As EBs differentiated at 1xg exhibited significantly increased expression of most terminal lineage markers that failed to appear to the same extent in  $\mu\text{g}$  samples, decreased expression of CDKN1A/p21 in  $\mu\text{g}$  samples compared with 1xg controls may be further evidence for decreased differentiation of EBs in  $\mu\text{g}$ . FGF1, which inhibits apoptosis and cell cycle arrest and also plays a role in embryonic development, was downregulated in  $\mu\text{g}$  samples, while FGF4, which promotes proliferation of mESCs [28], exhibited increased expression in  $\mu\text{g}$ -differentiated EBs compared with 1xg-differentiated EBs. Collectively, these gene expression data provide evidence for the hypothesis that cell cycle arrest occurs in EBs exposed to  $\mu\text{g}$  without the corresponding cell differentiation, possibly causing accumulation of partially differentiated cells ready for differentiation upon reloading.

To further characterize both the adhesion capacity and differentiation of EBs after reloading, we continued  $\mu\text{g}$ -exposed EB cultures on earth at 1 g for 9 days and quantified the differentiation of contractile cardiomyocytes as a method of evaluating differentiation [12,15,29]. Increased numbers of beating cardiomyocyte clusters in post- $\mu\text{g}$  culture and decreased expression of cardiomyocyte markers suggest that EBs differentiated in  $\mu\text{g}$  retained more stem cells and overall greater pluripotency as a result of not progressing normally through differentiation as seen in loaded 1xg control samples. Similar results have been seen in our bone marrow stem cell differentiation experiments in  $\mu\text{g}$ -exposed mice that resulted in increased osteoclastogenesis and osteoblastogenesis potential following reloading at 1xg [14].

To further investigate the hypothesis that EBs maintained greater stemness in  $\mu\text{g}$ , we conducted RT-qPCR analysis on stem cell markers, p53 pathway-related genes for cell survival, apoptosis and health, cell cycle regulation, and lineage and tissue type-specific markers.

Significant alterations were found in the Notch and Wnt signaling pathways, which play important roles during embryonic development, including cell fate regulation, cell proliferation, cell differentiation, and cell–cell communication [30–32]. Previous studies have also found alterations in Notch signaling in response to SMG. Specifically, SMG increases differentiation of liver stem cells into hepatocytes through activation of Bmp4/Notch1 signaling [12]. In sharp contrast, our  $\mu\text{g}$  experiments show significant downregulation in several Notch signaling genes important for the regulation of cell proliferation and developmental processes (Dvl1, Numb), while neural stem cell development genes were upregulated (DLL3). Interestingly, gene expression markers for neural stem cells and neural development, and terminal differentiation markers for mature neurons (SLC17A6, GALC, and MTAP2) were the only lineage-specific markers that were upregulated in  $\mu\text{g}$  compared to 1xg controls (Fig. 6). Previous research also showed increases in nervous system development genes in mesenchymal stem cells flown in space

for 9 days, including genes involved in neuron morphogenesis and transmission of nerve impulses and synapses [33]. However, other studies have shown the negative impact of mechanical unloading on neurogenesis in embryos [34], which may be attributed to impairment of neural migration rather than neural cell development [33]. These results show that neural cells may be one of few whose differentiation from stem cells is not inhibited in the  $\mu\text{g}$  environment.

Wnt signaling is known to be altered in  $\mu\text{g}$  conditions, although this pathway has mostly been studied in the context of bone formation [35]. In EBs differentiated in  $\mu\text{g}$ , the majority of Wnt pathway-related molecules were downregulated, indicating an overall downregulation of the signaling pathway due to unloading. As the Wnt signaling pathways are primarily involved in cell fate determination during embryogenesis and cell proliferation, our results suggest it may also modulate those functions in response to tissue load levels. WNT1 expression, however, increased in  $\mu\text{g}$  samples compared with 1xg. WNT1 can induce integrin-dependent differentiation of the neuro-ectoderm lineage, [36] and is also a positive regulator of cardiomyogenesis in mice, which when overexpressed leads to increased cardiomyocyte production and decreased hematopoiesis [37–40]. Increased WNT1 expression is consistent with the observed increased neural marker expression and increased numbers of contractile cardiomyocyte colonies in  $\mu\text{g}$  samples.

We also investigated stem cell lineage markers including those for embryonic, hematopoietic, mesenchymal, and neural stem cells in addition to stem cell-specific markers for processes such as metabolism, adhesion, communication, and self-renewal (Figs. 4 and 6). Expression of growth factors associated with stem cell differentiation were significantly decreased in EBs differentiated in  $\mu\text{g}$  compared with 1xg, while expression of self-renewal and pluripotency markers (such as SOX1 and SOX2) was less downregulated in  $\mu\text{g}$  samples compared with 1xg, indicating partial maintenance of “stemness”.

In contrast, previous studies using SMG have shown decreased “stemness” and increased differentiation in ESCs [41], which may further highlight the discrepancy between modeled  $\mu\text{g}$ /SMG and true  $\mu\text{g}$  experienced during spaceflight. Since early differentiation of ESCs is associated with signaling via the MAPK pathway, and since this pathway is also associated with mitogenic matrix-integrin-kinase mechanotransduction, it is possible that increased fluid flow in rotating vessels/SMG models may activate signaling that could cause the reported increases in differentiation of stem cells.

One highly downregulated stem cell-specific marker found in  $\mu\text{g}$  samples was GJB1, a membrane-spanning protein that forms gap junction channels responsible for signal transduction between neighboring cells through diffusion of molecules such as ions ( $\text{K}^+$  and  $\text{Ca}^{2+}$ ), second messengers (IP3 and cAMP), and small metabolites (glucose). Mechanical stimulation causes synthesis of the second messenger molecule, IP3,  $\text{Ca}^{2+}$  release from intracellular stores, and passage of the  $\text{Ca}^{2+}$  through gap junctions [42]. Calcium signaling can modulate a number of cell functions such as transcription, proliferation, differentiation, and apoptosis [43,44]. Suppression of GJB1 may disrupt ion channel-based cell communication associated with differentiation.

Among hematopoietic stem cell differentiation markers investigated, increased expression of WNT1 that may cause

suppression of hematopoietic progenitor cell differentiation was found. In addition, terminal differentiation markers for monocytes (CCR5) and macrophages (EMR1) were also significantly downregulated, possibly contributing to the suppression of hematopoietic stem cell differentiation observed in microgravity [14,45–48]. Mesenchymal early stem cell markers including COL1A1, PPAR $\gamma$ , COL9A1, and ACAN, in addition to late differentiation markers for mesenchymal stem cell lineages were also found to be downregulated in EBs differentiated in  $\mu$ g, including bone, muscle, and cartilage markers. While adult bone tissue readily degenerates in  $\mu$ g [49], in EBs we also find downregulation of terminal bone differentiation markers (including CTSK, CALCR, and BGLAP) suggesting early embryonic effects of unloading on bone tissue.

Cartilage-specific differentiation markers, COMP and COL10A1, were also altered in EBs differentiated in  $\mu$ g (Fig. 6). Cartilage formation is known to be inhibited in microgravity [50]; however, the question remains as to whether decreased cellular activity in cartilage is due to decreased activities of mature cells or an inhibition of differentiation [51]. Muscle is another tissue that is affected by spaceflight-associated  $\mu$ g mechanical unloading, which results in increased muscle degeneration in response to unloading-induced disuse [52–55]. The downregulation of CAV3, TAGLN, and SMTN in  $\mu$ g-differentiated EBs compared with 1xg-differentiated EBs may indicate a decreased ability of stem cells to differentiate into smooth muscle.

Decreased gene expression for terminal lineage markers associated with the cardiovascular system, kidneys, and lymphatic system were also noted in  $\mu$ g EBs (Fig. 6). Specifically, we found decreases in the expression of venous, arterial, and lymphatic endothelium genes including NR2F2, NRP2, NRP1, DLL4, EFNB2, and LYVE1. Vascular endothelial cells are required for functions such as fluid filtration, hemostasis and hormone trafficking, and regulation of the muscle tone in the lumen of blood vessels [56]. Decreased expression of AQP1 and CYP27B1, important molecules for kidney development [57], was also observed in  $\mu$ g, indicating possible alterations to renal development and function during spaceflight.

Finally, alterations in the differentiation of tissues from the ectoderm and endoderm germ layers were also observed in  $\mu$ g. Specifically, epidermal lineage markers including KRT1, KRT14, and KRT15, were downregulated while expression of PMEL, a protein expressed in pigment cells, was upregulated in  $\mu$ g compared with 1xg controls. As keratins are generally found in late stages of epidermal differentiation, it is possible that increased PMEL expression in  $\mu$ g samples indicated that initiation of epidermal development occurs in  $\mu$ g but terminal differentiation processes are inhibited [58]. Most terminal differentiation markers for the liver, lung, and pancreas that were investigated in this study also failed to be expressed, or exhibited decreased expression in  $\mu$ g compared with 1xg controls.

## Conclusions

The experiments outlined here aimed to investigate the effects of  $\mu$ g during spaceflight on the ability of mESCs to differentiate and generate the cell lineages present in terminally differentiated tissues as a model for adult stem cell-based tissue regeneration. To address this question, we ana-

lyzed the influence of  $\mu$ g on early lineage commitment of stem cells by investigating the ability of EBs to differentiate and develop during the 15 day STL spaceflight experiment in  $\mu$ g. We found that exposure to  $\mu$ g inhibits the ability of EBs to differentiate and express terminal differentiation markers for most lineages of the three primary germ layers, including bone, muscle, immune system, renal system, liver, lung, and pancreas (Fig. 6). Furthermore, EBs differentiated in  $\mu$ g maintained expression of self-renewal markers, indicating partial retention of stem cell properties. EBs differentiated in  $\mu$ g appeared to initiate the differentiation process but failed to express normal terminal differentiation markers expressed in mechanically loaded tissues. This inhibition of differentiation may be mediated both by incomplete commitment of early stem cell progenitors to the path of differentiation, and later by decreased calcium channel-mediated mechanotransduction signaling. This inhibition of differentiation may not only have significant implications for understanding development in the context of mechanical loading, but also for regeneration of adult mammalian tissues from tissue-specific stem cells. These results provide further evidence for the hypothesis that mechanical unloading of cells and tissues in  $\mu$ g inhibits the proliferation and differentiation of stem cells resulting in decreased stem cell-based tissue regenerative potential in space and under disuse conditions.

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## Author Disclosure Statement

The principal investigator (PI) holds a NASA civil servant Research Scientist position that is similar in nature to a university tenured faculty position that does not depend on the opinions expressed by the scientist. In addition, the NASA funding supporting this work was externally competed based on external scientific peer review, and not intramural review and/or funding that might influence the findings. All other authors were either supported by the PI grant funding or by entities other than NASA such as UNSW. As such, no real competing financial interests exist.

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Address correspondence to:  
*Dr. Eduardo A.C. Almeida*  
*Space Biosciences Division*  
*NASA Ames Research Center*  
*Mail Stop 236-7*  
*Moffett Field, CA 94035*

*E-mail:* e.almeida@nasa.gov

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