Direct Evaluation of Myocardial Viability and Stem Cell Engraftment Demonstrates Salvage of the Injured Myocardium

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Rationale: The mechanism of functional restoration by stem cell therapy remains poorly understood. Novel manganese-enhanced MRI and bioluminescence reporter gene imaging were applied to follow myocardial viability and cell engraftment, respectively. Human-placenta–derived amniotic mesenchymal stem cells (AMCs) demonstrate unique immunoregulatory and precardiac properties. In this study, the restorative effects of 3 AMC-derived subpopulations were examined in a murine myocardial injury model: (1) unselected AMCs, (2) ckit+AMCs, and (3) AMC-derived induced pluripotent stem cells (MiPSCs).

Objective: To determine the differential restorative effects of the AMC-derived subpopulations in the murine myocardial injury model using multimodality imaging.

Methods and Results: SCID (severe combined immunodeficiency) mice underwent left anterior descending artery ligation and were divided into 4 treatment arms: (1) normal saline control (n=14), (2) unselected AMCs (n=10), (3) ckit+AMCs (n=13), and (4) MiPSCs (n=11). Cardiac MRI assessed myocardial viability and left ventricular function, whereas bioluminescence imaging assessed stem cell engraftment during a 4-week period. Immunohistological labeling and reverse transcriptase polymerase chain reaction of the explanted myocardium were performed. The unselected AMC and ckit’AMC–treated mice demonstrated transient left ventricular functional improvement. However, the MiPSCs exhibited a significantly greater increase in left ventricular function compared with all the other groups during the entire 4-week period. Left ventricular functional improvement correlated with increased myocardial viability and sustained stem cell engraftment. The MiPSC-treated animals lacked any evidence of de novo cardiac differentiation.

Conclusion: The functional restoration seen in MiPSCs was characterized by increased myocardial viability and sustained engraftment without de novo cardiac differentiation, indicating salvage of the injured myocardium. (Circ Res. 2015;116:e40-e50. DOI: 10.1161/CIRCRESAHA.116.304668.)

Key Words: magnetic resonance imaging ■ molecular imaging ■ multimodal imaging

Multiple human stem cell populations have demonstrated the ability to improve left ventricular ejection fraction (LVEF) after myocardial damage. These cells include pluripotent human embryonic stem cells (ESCs), human induced pluripotent stem cells (iPSCs),1,2 bone marrow stem cells, mesenchymal stem cells, and cardiac progenitor cells.1,3,4 Initial studies hypothesized that the improved LVEF was because of the spontaneous cardiac differentiation of the stem cells and regeneration of the injured myocardium (regeneration hypothesis).7 However, increasing evidence has refuted differentiation of the engrafted stem cells.8,9 Instead, careful analysis of the data suggested that the paracrine effects salvaged the injured myocardium without de novo cardiac differentiation or myocardial regeneration (salvage hypothesis).5,9 In support of the salvage hypothesis, multiple studies have demonstrated similar improvements with conditioned media, secreted cell products, or cell lysis when compared with intact stem cells.3,10-12

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The pluripotency states of the stem cell are theorized to correlate directly with myocardial restoration potential. However, few studies have conducted head-to-head comparisons of the restorative processes of different stem cell populations and assessed their direct effects on the myocardial viability in vivo. In a comparison study of murine ESCs versus mesenchymal stem cells in postischemic injury, the ESCs demonstrated greater functional recovery when compared with mesenchymal stem cells. The investigation suggested that the greater restorative potential of the ESCs was because of the increased paracrine signaling with enhanced production of vascular endothelial growth factor (VEGF), interleukin (IL)-10 and IGF-1 (insulin-like growth factor) in the ESC-treated hearts. However, the direct effect of paracrine signals on myocardial viability and the biological role of stem cell engraftment were not evaluated.

We examined the therapeutic effects of 3 subpopulations of amniotic mesenchymal stem cells (AMCs) derived from the human placenta. AMCs are derived from the inner cell mass of the embryo, which differentiate into the epiblast and the hypoblast on days 8 to 9 of embryological development. The epiblast gives rise to the extraembryonic mesoderm-like mass of the embryo, which differentiate into the epiblast and the hypoblast on days 8 to 9 of embryological development. The epiblast gives rise to the extraembryonic mesoderm-like AMCs in the amniotic membrane, which retain pluripotent gene expression. These stem cells differentiate predominantly along the mesodermal lineage and have propensity for cardiac lineage specification by the expression of the ckit cell surface marker associated with cardiac progenitor cells. In addition, these cells line the amniotic membrane situated at the maternal–fetal interface, conferring the critical immunomodulatory properties for the fetus. Three cell subpopulations were generated from this common lineage to directly compare their therapeutic potential: (1) unselected AMCs (uAMCs), (2) ckit+AMCs (c+AMCs), and (3) AMC-derived induced pluripotent stem cells (MiPSCs). This study hypothesized that the MiPSCs would have the greatest cardiac restorative potential because of their pluripotency.

Manganese-enhanced MRI (MEMRI) enables viability-specific evaluation of the myocardium. This novel technique was integrated with delayed-enhanced MRI (DEMRI) to measure the direct therapeutic impact of the stem cells on myocardial viability and to correlate with sensitive in vivo bioluminescence imaging (BLI) of stem cell engraftment. This integrated in vivo imaging platform allowed real-time evaluation of the direct biological effects of the engraftment of AMC derivatives on the viable, injured, and nonviable myocardium volume at high temporal and spatial resolution.

This study demonstrated that myocardial viability paralleled differential engraftment of each AMC subpopulation and correlated with the degree of salvage of the injured myocardium.

**Methods**

Detailed methods are provided in the Online Data Supplement.

**Isolation of AMCs From the Human Placentas**

A placenta from 1 healthy subject was obtained. uAMCs were enzymatically isolated from the amniotic membrane.

**Fluorescent-Activated Cell Sorting**

The uAMCs underwent 2-step fluorescent-activated cell sorting with ckit and SSEA-4 antibodies. The sorted cells were labeled c+AMCs.

**BLI Reporter Gene Virus Transduction**

A BLI reporter gene plasmid DNA (courtesy of Joseph Wu, Stanford University) was isolated using the plasmid Maxi-kit (Qiagen, Inc, CA). 293FT cells were then transfected. The supernatant was collected and centrifuged to obtain the pellets used for transduction.

**Virus Production and iPSC (MiPSC) Generation**

The plasmid of pHAGE2EF1-OKSM (courtesy of G. Mostoslavsky, Boston University) was used to generate the virus. 293FT cells were then transfected. The virus was harvested for 3 days and concentrated by centrifugation. AMCs were transduced with the concentrated virus. These cells were then passaged on day 6 and cultured on plates preseeded with irradiated mouse fibroblasts. The cells were grown until the formation of spontaneous colonies.

**Permanent Left Anterior Descending Artery Ligation**

Animal care and interventions were done in accordance with the Laboratory Animal Welfare Act and all animals received humane care and treatment in accordance with the Guide for the Care and Use of Laboratory Animals (www.nap.edu/catalog/5140.html). Immunotolerant SCID (severe combined immunodeficiency)-beige male mice (90–120 days; Charles River Laboratories, Inc, MA) were anesthetized in an isofluorane inhalational chamber and endotracheally intubated with a 20-gauge angiocatheter (Ethicon Endo-Surgery, Inc, OH). Ventilation was maintained with a Harvard rodent ventilator (Harvard Apparatus, Inc, MA). Acute myocardial infarction was created by ligation of the mid–left anterior descending coronary artery through a left thoracotomy. The mice were randomly allocated to 4 groups. The mice received one of the following cell types or normal saline directly into the peri-infarct region immediately after induction of acute myocardial infarction: (1) normal saline control (n=9), (2) uAMCs (n=9), (3) c+AMCs (n=8), and (4) MiPSCs (n=9). The cells were injected into the peri-infarct region with a Hamilton syringe containing 250000 cells suspended in a 20 μL volume of a 1:5 mixture of Matrigel (BD Biosciences, CA) and cell dissociation buffer (Sigma) to prevent clumping of cells. Cell dissociation buffer was used to prevent cell clumping. The chest was closed in 2 layers with 5-0 Vicryl suture (Ethicon).

**In Vivo MRI**

Mice were serially imaged by cardiac MRI at weeks 1, 2, and 4 after left anterior descending artery ligation and treatment. Mice were anesthetized during the examination and electrocardiographic gating obtained with 2 subcutaneous precordial leads. LV function was evaluated with fast spoiled gradient echo sequences. MEMRI...
and DEMRI used fast gradient echo inversion recovery sequences. MEMRI was obtained after intraperitoneal injection of manganese solution. The following day, DEMRI was obtained after intraperitoneal injection of gadopentetate dimeglumine. Images were analyzed offline. Peri-infarct region was defined as the region of overlap between DEMRI enhancement and MEMRI defect, representing the area of viable myocardium (MEMRI) in the region of nonviable myocardial scar (DEMRI) as shown previously.13 Percent MEMRI scar volume=MEMRI defect volume/total LV mass volume; % MEMRI viable myocardial volume=MEMRI enhancement volume/total LV mass volume; % DEMRI scar volume=DEMRI scar volume/total LV mass volume; % DEMRI-MEMRI peri-infarct volume=DEMRI–MEMRI peri-infarct volume/total LV mass volume.

In Vivo Optical BLI

Optical BLI was performed 15 to 25 minutes after d-luciferin intraperitoneal injection (400 mg/kg; Xenogen, MA) with 3 to 5 minute acquisition scans on a charge-coupled device camera (IVIS 200; Xenogen). Peak area from a fixed time of interest was evaluated with Living Image 3.2 software (Xenogen).

Immunohistology

Hearts were flushed with normal saline, fixed with paraformaldehyde, and embedded in paraffin blocks. A total of 4-μm slices were sectioned and then stained with hematoxylin and eosin. Unstained paraffin embedded sections were deparaffinized and rehydrated. Sections underwent antigen unmasking, treatment with Triton-X 100 and blocking with BSA and normal goat serum. MiPSCs and c+AMCs of human origin were detected in murine myocardium using primary antibodies specific for human mitochondria. Primary antibodies specific for cardiomyocytes and endothelial cells were also detected using a goat anti-human IgG1 AlexaFluor 488 Ab. A rabbit polyclonal antibody to ckit was used and visualized with goat anti-rabbit IgG Alexa Fluor 488. The cellular cytoskeleton was counterstained with AlexaFluor 568 Phalloidin. Finally, luciferin was immunostained by incubating rabbit anti-firefly luciferase and anti–human nuclear antigen and visualized with anti-rabbit Alexa Fluor 488 and anti-mouse Cy3 secondary antibodies.

Luminex Immunoassay

The human 63-plex magnetic bead kit (eBiosciences/Affymetrix, CA) was used according to the manufacturer’s recommendations with modifications as described below. Briefly, the beads were added to a 96-well plate and washed in a washer solution (BioTek ELx405, VT). Samples were added to the plate containing the mixed antibody-linked beads and incubated at room temperature for 1 hour followed by overnight shaking incubation at 4°C. Cold and room temperature incubation steps were performed on an orbital shaker at 500 to 600 rpm. After overnight incubation, the plates were washed and then biotinylated with detection antibody for 75 minutes at 50°C. Streptavidin-PE was added. After incubation for 30 minutes at room temperature, another wash was performed and reading buffer was added to the wells. Fluorescence intensity of each sample was measured in duplicate. Plates were read using a Luminex 200 instrument with a lower bound of 50 beads per sample per cytokine. For quality control, custom assay control beads (Radix Biosolutions, TX) were added to all wells.

Real-Time Reverse Transcription Polymerase Chain Reaction

Total RNA was extracted from the 3 cell subpopulations (uAMCs, c+AMCs, and MiPSCs) using Trizol reagent (Invitrogen) according to the manufacturer’s recommendation. A total of 2 0.05g of total RNA was transcribed into cDNA using Superscript first strand synthesis system (Invitrogen). The polymerase chain reaction (PCR) products were size fractionated by 2% agarose gel electrophoresis (Invitrogen). Genes were amplified using IQ SYBR Green Supermix (Applied Biosystems, MA) and StepOne Plus Real-Time PCR Detection System (Applied Biosystems). All genes were amplified for 40 cycles. Specific gene expression was first normalized to GADPH and then compared with control groups. Relative measurement for human primers was performed for the following: KLF4, NANOG, EBAF, MYC, SOX2, TDGF1, OCT4, GATA4, atrial natriuretic peptide (ANP), cardiac muscle troponin T (CTNT), cardiac muscle troponin I (CTNI), α-myosin heavy chain (α-MHC), NXX2.5 (Invtrogen), KLF4, NANOG, EBAF, MYC, SOX2, TDGF1, and OCT4 are previously described ESC pluripotency genes.17 NXX2.5 and GATA4 are transcription factors associated with heart field–specific progenitors and embryonic cardiomyocytes,18 whereas ANP, CTNT, CTNI, and α-MHC are mature cardiac-specific cell marker genes.19,20

In addition, total mRNA was isolated from the cell-treated and control myocardial tissue at the end of the study. Total mRNA was then reverse transcribed into cDNA. Real-time quantitative PCR was run on a 96-well real-time PCR thermocycler using Power SYBR Green master mix (Applied Biosystems), according to the manufacturer’s recommendations. Relative measurement for mouse primers was performed for the following: collagen I, collagen III, connective tissue growth factor, transforming growth factor (TGF), fibronectin, and Akt. The GADPH housekeeping gene was used as reference for the relative quantification of the genes of interest.21

Telomerase Activity and Telomere Length

Telomerase activity was measured using the nonradioisotopic method of the TRApeze Telomerase Detection Kit (S7700; EMD Millipore, MA). The products were stained with SYBR Gold Nucleic Acid Gel Stain (Life Technologies, NY) and run on a 15% polyacrylamide gel in 1x TBE. Telomere length was measured by SpectraCell Laboratories, Inc (TX). Genomic DNA was extracted from 500000 cells using phenol chloroform and quantified using the Quant-IT PicoGreen dsDNA Assay Kit (Life Technologies). Telomere length analysis was performed at SpectraCell Laboratories Inc using a CLIA (clinical laboratory improvement amendments)-approved, high-throughput quantitative PCR assay.22 The assay determines a relative telomere length by measuring the factor by which the sample differs from a reference DNA sample in its ratio of telomere repeat copy number to singe gene (36B4) copy number. All samples were run in quadruplicate with ≥1 negative control and 2 positive controls of 2 different known telomere lengths (high and low). The results were reported as a telomere score equivalent to the average telomere length in kilo base pair.

Statistical Analysis

Results are mean±SEM. Significant differences (P<0.05) were tested using ANOVA and Bonferroni post-test for ≥2 groups or time points, and Student unpaired t test for 2 groups. The Pearson correlation coefficient was assessed. The correlation between LVEF and viable myocardium by MEMRI, LVEF, and myocardial scar by DEMRI and LVEF and stem cell engraftment by BLI.

Results

LV Systolic Function Correlates With Stem Cell Engraftment

One week after acute myocardial infarction, all treated mice demonstrated improved LVEF compared with control (Figure 1A). However, the initial LVEF increase in the uAMC group (26.9±1.5% versus 17.9±0.2%, week 1; P<0.01) did not persist and was not significantly different from control (normal saline) at weeks 2 and 4. The initial functional improvement and subsequent decline paralleled the engraftment pattern of the transplanted uAMCs as measured by BLI (Figure 2A). The c’AMC group exhibited significant improvement at weeks 1 and 2 but did not persist through week 4 compared with the control group (23.1±2.0% versus 19.0±1.3%, week 4; P=0.1). This intermediate restorative capability also paralleled the engraftment of the c’AMCs
Conversely, the MiPSC-treated mice had sustained improvement in LVEF throughout the 4 weeks compared with control (30.0±0.98% versus 19.0±1.3%, week 4; P<0.01; Figure 1B). Furthermore, the MiPSC group demonstrated significantly improved LVEF compared with control throughout weeks 1 and 2. The control group showed severely depressed LVEF that was unchanged throughout the study. B, Short axis acquisitions are shown during end-diastole and end-systole at the mid-LV. The MiPSC-treated mouse demonstrated increased contractility compared with control. *P<0.05, **P<0.01 vs control by unadjusted Student t test.

MEMRI of Viable Myocardium and DEMRI of Infarct Scar

To quantify the contribution of the stem cells to the myocardium, myocardial viability was assessed directly by MEMRI and infarct scar by DEMRI. The uAMC-treated group had a significant increase in percent viable myocardial volume at week 1 compared with the control arm (85.6±0.6% versus 75.2±1.0%; P<0.01; Figure 3A). However, this difference did not persist to week 4.

MiPSC group compared with control (not shown). No significant difference in the end-diastolic volumes was seen between the treated and control groups.
Similarly, DEMRI measurement of percent scar volume was decreased significantly compared with control at week 1 (27.6±1.2% versus 32.6±0.7%; *P* <0.01; Figure 3C) but not sustained through week 4. Myocardial viability and infarct scar size paralleled the engraftment kinetics of the uAMCs. There was no significant difference between the peri-infarct volumes when comparing the uAMC versus control groups at week 4.

The c+AMC-treated mice initially had increased percent viable myocardial volume up to week 2 as measured by MEMRI (84.2±2.7% versus 75.8±1.1%; *P* <0.05; Figure 3A) but this increase did not persist to week 4 (78.9±1.2% versus 74.5±1.7%; *P* =0.16). DEMRI measurement of scar volume trended toward decreased scar volume at week 4 (31.0±5.2% versus 32.8±0.9%; *P* =0.75; Figure 3C). These findings also paralleled the engraftment kinetics of c+AMCs. No significant difference in the DEMRI–MEMRI peri-infarct volumes was observed between the c+AMC and control groups at week 4 (9.8±3.2 versus 7.3±1.3; *P* =0.49).

However, the MiPSC arm demonstrated a significant and persistent increase in the direct MEMRI measurement of percent viable myocardial volume compared with the control arm throughout the 4-week period (89.1±0.7% versus 74.5±1.7%, week 4; **P** <0.01; Figure 3A and 3B). DEMRI scar volume was also significantly decreased compared with the control arm up to week 4 (21.4±1.3% versus 32.8±0.9%; *P* <0.01; Figure 3C). These findings paralleled the sustained engraftment of MiPSCs. The peri-infarct volume, however, demonstrated no significant difference when compared with the controls (10.5±2.0% versus 7.3±1.3%; *P* =0.21).

Finally, significant correlation was found when analyzing the relationship between the 3 imaging parameters (MEMRI, BLI, and DEMRI) and functional restoration (LVEF) in the 3 treatment groups. First, there was a positive correlation between viable myocardium measured by MEMRI and LVEF with a Pearson correlation coefficient of 0.78 (*P* <0.01). Second, there was a positive correlation between stem cell engraftment demonstrated by BLI and LVEF with a Pearson correlation coefficient of 0.74 (*P* <0.01). Third, there was a negative correlation between myocardial scar by DEMRI and LVEF with a Pearson correlation coefficient of −0.66 (*P* <0.05).

**Immunohistological Validation of Stem Cell Engraftment Signal**

Immunohistology of the MiPSC-treated heart tissue sections at week 4 demonstrated successful engraftment of the MiPSCs with positive staining of human mitochondrial antibody (Figure 4A). Immunohistology using human anti–cardiac troponin T and anti-CD31 (PECAM-1 [platelet endothelial cell adhesion molecule]) antibodies did not demonstrate evidence of cardiac or endothelial differentiation, respectively (Figure 4B). Immunohistology of the c+AMC-treated heart tissue sections at week 4 demonstrated successful engraftment of the c+AMCs with positive staining of both human mitochondrial antibody and ckit receptor antibody (Figure 4C and 4D). However, immunohistology using anti–cardiac troponin T and anti-CD31 antibodies did not demonstrate evidence of cardiac
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The uAMCs and c+AMCs, confirming their pluripotent status. MiPSCs demonstrated high expression of pluripotency genes (OCT4, SOX2, TDGF1, NANOG, MYC, and EBAF) compared with uAMCs. Similarly, c+AMCs showed increased production of 11 cytokines when compared with uAMCs: FASL, LIF (leukemia inhibitory factor), PGF1, IL1RA, TGF-β, IL9, TNF-α, ICAM1, VCAM1, FGF-B, PAI1, and ENA78 are significantly upregulated in MiPSCs compared with c+AMCs. These findings underlie the enhanced engraftment of MiPSCs. Corresponding in vivo expression of molecular markers of apoptosis (Akt), fibrosis (collagen I, collagen III, connective tissue growth factor, TGF-β, and fibronectin), angiogenesis (VEGF), inflammation (TNF-α), and early cardiac differentiation (Nkx2.5) was measured at week 4 from the myocardial tissue in the 4 groups. Consistent with the Luminex assay, reverse transcriptase PCR demonstrated a trend toward increased expression of TNF-α in both MiPSC and c+AMC groups. In addition, Nkx2.5 was significantly increased in the c+AMC group (Figure 6B).

Ex Vivo Analysis of Paracrine Factors

To better elucidate the myocardial salvage mechanism, the supernatant of each subpopulation underwent 63-plex Luminex Immunoassay of human cytokines. Significant differences in the production of 15 cytokines in the supernatant of MiPSCs and 10 cytokines in c+AMCs were detected when compared with uAMCs (P<0.05; Figure 6A). The significant production of cytokines in the MiPSCs could be classified into the following categories: (1) antiapoptosis (Fas ligand [FASL], IL9, BDNF [brain-derived neurotrophic factor]), (2) antifibrosis (plasminogen activator inhibitor-1 [PAI1], TGF-β), (3) proangiogenesis (VEGF, fibroblast growth factor-B [FGF-B], placental growth factor-1 [PGF1]), and (4) anti-inflammation (IL1A, IL1B, IL1RA, intercellular adhesion molecule-1 [ICAM1], vascular cell adhesion molecule-1 [VCAM1], tumor necrosis factor [TNF]-α, MCP1 [monocyte chemoattractant protein-1], ENA78). Specifically, IL1B, TGF-β, IL9, TNF-α, ICAM1, VCAM1, FGF-B, PAI1, and ENA78 are significantly upregulated in MiPSCs compared with c+AMCs. These findings underlie the enhanced engraftment of MiPSCs. Similarly, c+AMCs showed increased production of 11 cytokines when compared with uAMCs: FASL, LIF (leukemia inhibitory factor), PGF1, IL1RA, TGF-β, IL9, TNF-α, ICAM1, VCAM1, FGF-B, PAI1, and ENA78 are significantly upregulated in MiPSCs compared with c+AMCs. These findings may explain their higher engraftment potential when compared to the uAMCs.

Corresponding in vivo expression of molecular markers of apoptosis (Akt), fibrosis (collagen I, collagen III, connective tissue growth factor, TGF-β, and fibronectin), angiogenesis (VEGF), inflammation (TNF-α), and early cardiac differentiation (Nkx2.5) was measured at week 4 from the myocardial tissue in the 4 groups. Consistent with the Luminex assay, reverse transcriptase PCR demonstrated a trend toward increased expression of TNF-α in both MiPSC and c+AMC groups. In addition, Nkx2.5 was significantly increased in the c+AMC group (Figure 6B).

Pluripotency, Telomerase Activity, and Telomere Length

Reverse transcriptase PCR was performed on MiPSCs, c+AMCs, and uAMCs (Figure 7A). Gene expression values are shown in relative units compared with uAMCs. MiPSCs demonstrated high expression of pluripotency genes (OCT4, SOX2, TDGF1, NANOG, MYC, and EBAF) compared with uAMCs and c+AMCs, confirming their pluripotent status. There was no differential pattern of expression with respect to cardiac-specific transcription factors (Nkx2.5, CTNI, α-MHC, CTNT, and ANP) when comparing the MiPSCs and from the human cells, the MiPSCs were costained with anti-luciferase antibody and human nuclear antibody (Figure 4G). Robust colocalization of the 2 immunostains confirms the origin of the BLI signal from the transplanted human stem cells.

Of note, hematoxylin and eosin-stained sections of the myocardium demonstrated teratoma formation in all the mice in the MiPSC group as expected. The teratoma, however, were less invasive by gross histological visualization compared with our prior experience with murine and human ESCs (Figure 5). There was no teratoma formation seen in the other groups.

**Figure 4.** Immunohistology at the site of cell injection in amniotic mesenchymal stem cell (AMC)-derived induced pluripotent stem cell (MiPSC) and ckit+AMC (c+AMC)-treated mice. A, MiPSCs showed successful engraftment by the detection of human mitochondrial antibody (green, white arrows) at the site of cell injection. B, Immunostaining with cardiac troponin T antibody (green) did not demonstrate any signal within the engrafted MiPSCs (light blue) and labeled only the native murine myocardium. C, c+AMCs showed successful engraftment by human mitochondrial antibody (green, white arrow). D, Persistent ckit+ expression was confirmed by ckit+ receptor antibody (green, white arrow). E and F, However, immunostaining using cardiac troponin T (green, white arrow) and PECAM (platelet endothelial cell adhesion molecule) antibodies did not colocalize with the human mitochondrial or ckit+ stain demonstrating no evidence of cardiac or endothelial differentiation, respectively. Nuclear counterstain (blue) and F-actin (red) antibodies were used to visualize the cellular cytoskeleton. G, Merged and monochrome images of the MiPSCs costained with antiluciferase antibody (FLUC [firefly luciferase]), human nuclear antibody (HNA), and Hoechst 33342 (DNA). Robust colocalization of the 3 immunostains confirms the origin of the bioluminescence reporter gene imaging signal from the transplanted human stem cells.
cAMCs to uAMCs. Furthermore, the telomerase activity and telomere length were measured for the 3 cell subpopulations. There was a significant increase in the telomerase activity for the MiPSC group, providing an additional parameter to explain for the prolonged engraftment. Telomere lengths were not significantly different for the 3 groups (Figure 7B and 7C).

**Discussion**

Cardiomyocyte death or dysfunction after acute myocardial infarction results in pathological remodeling of the LV and eventual heart failure. Despite reports of restorative potential of cell-based therapies for the injured myocardium, real-time in vivo monitoring of regeneration of de novo myocardium or salvage of the in situ myocardium has not been possible.\(^{16,21,24–26}\) In this study, we evaluated in vivo myocardial viability and stem cell engraftment directly to track the salvage of the injured myocardium using a novel multimodality imaging approach. Regeneration requires functional restoration, enhanced myocardial viability, and sustained engraftment with evidence of de novo cardiac differentiation.\(^{8}\) Conversely, salvage requires functional restoration, enhanced myocardial viability, and engraftment signal without evidence of de novo cardiac differentiation.\(^{8,27}\) This study tested the salvage hypothesis that the enhanced stem cell engraftment will increase myocardial viability and restore the function of the injured myocardium. The 3 subpopulations derived from a common stem cell lineage were studied: (1) uAMCs, (2) cAMCs, and (3) MiPSCs. These cells were transduced with luciferase reporter gene, which enabled reliable detection of stem cell engraftment by BLI. MEMRI and DEMRI were used to directly quantify myocardial viability and scar size. MEMRI uses the unique property of manganese (Mn\(^{2+}\)), which enters only the extracellular space to delineate the scar.\(^{15}\)

The 3 AMC subpopulations demonstrated variable functional improvement of the injured myocardium during the 4-week period. In the uAMC-treated group, the initial recovery in function and viability was only seen transiently, which paralleled the nonengraftment or death of the transplanted stem cells. The cAMC-treated mice demonstrated intermediate improvement in both LVEF and myocardial viability. Although these cells exhibited increased upregulation of NKX2.5, consistent with early cardiac progenitor phenotype,\(^{28}\) significant functional improvement, myocardial viability, and cellular engraftment did not persist throughout the 4-week duration of the study. Sustained restoration was seen only in the MiPSC group, which exhibited significant increase in the viable myocardium by MEMRI and continued cell engraftment by BLI during all 4 weeks. This persistent increase in myocardial viability and cell engraftment without any evidence of cardiac differentiation in the MiPSC group is consistent with myocardial salvage as opposed to regeneration as the mechanism underlying sustained improvement in LVEF.

In support of salvage of the myocardium by the stem cells, the human cytokine 63-plex Luminesx analysis demonstrated a significant increase in paracrine factors, including 15 anti-inflammatory, antiapoptotic, antiangiogenic, and proangiogenic factors from the MiPSCs and 10 from the cAMCs. Specifically, there were >9 factors (IL1B, TGF-β, IL9, TNF-α, ICAM1, VCAM1, FGF-B, PAl1, and ENA78), which MiPSCs expressed >2-fold increase when compared with cAMCs. These findings were substantiated by the PCR analysis of the explanted myocardium, which exhibited a similar trend toward upregulation of the related genes. Specifically, TNF-α, a cytokine with multiple effects, which includes the antiapoptotic effects via activation of nuclear factor-xB, had increased signal by both cytokine and gene expression.\(^{29}\) The sustained MiPSC engraftment and enhanced myocardial viability remained steady throughout the 4-week period, which most likely led to persistent paracrine effect to improve the LVEF. The findings that uAMCs show minimal while cAMCs show intermediate evidence of salvage are consistent with our model that the decreased production of paracrine factors is commensurate with their limited engraftment. Finally, increased telomere activity was observed which does not necessarily correlate with telomere length. Telomere length is regulated by factors in addition to telomerase activity,\(^{30–33}\) including cis-acting regulators of association of telomerase with telomeres,\(^{34}\) mitotic rate, and oxidative stress.\(^{35}\) Telomere length is the net outcome of competing telomere shortening and lengthening events over the history of a cell lineage, and thus may not correlate with telomerase activity at 1 time point. iPSC-derived cells may have variable telomere length but the presence of increased...
Figure 6. A, The 63-plex Luminex Immunoassay of human cytokines detected significant increase in the production of 15 cytokines in the supernatant of amniotic mesenchymal stem cell (AMC)–derived induced pluripotent stem cells (MiPSCs) and of 10 cytokines in c-kit+AMCs (c+AMCs) when compared with unselected AMCs (uAMCs; *P<0.05; A). The significant production of cytokines in the MiPSCs was involved in antiapoptosis (Fas ligand [FASL], interleukin [IL]-9, brain-derived neurotrophic factor [BDNF]), antifibrosis (plasminogen activator inhibitor-1 [PAI1], transforming growth factor-B [TGF-B], proangiogenesis (vascular endothelial growth factor [VEGF], fibroblast growth factor-B [FGF-B], placental growth factor-1 [PIGF-1]), and anti-inflammation (IL1A, IL1B, IL1R, intercellular adhesion molecule-1 [ICAM1], vascular cell adhesion molecule-1 [VCAM1]), tumor necrosis factor [TNF]-α, MCP1 [monocyte chemoattractant protein-1], ENA78). Similarly, c+AMCs showed increased production of 11 cytokines when compared with uAMCs: FASL, leukemia inhibitory factor (LIF), PIGF, IL1R, TGF-β, IL9, TNF-α, IL1A, VCAM1, FGF-B, PAI1 (*P<0.05). B, Effects of cell therapy on paracrine factor gene expression in the explanted myocardium as assayed by reverse transcriptase polymerase chain reaction (RT-PCR). Expression of fibrotic (collagen 1, collagen 3, fibronectin, and Akt), apoptotic (TNF-α), angiogenic (VEGF), inflammatory (TGF-β), and cardiac-specific (NCKX2.5) genes were evaluated by RT-PCR at 4 weeks. Fibronectin, TNF-α, VEGF, and NCK2.5 showed a trend toward differential gene expression in cell-based therapy–treated groups compared with control. Only NCKX2.5 gene expression in the c+AMC group demonstrated a significant increase compared with control (P=0.04). *P<0.05 vs control.
telomerase activity in the MiPSCs provides definitive evidence of reprogramming of the cells. Based on these data, this study confirms that the MiPSCs enhance stem cell engraftment that leads to increased production of the paracrine factors to salvage the injured myocardium without any histological evidence of cardiac differentiation.

Limitation

The 3 cell subpopulations, derived from identical cell lineage, provided an optimal model to compare the restorative impact on the myocardium by stem cells with varying pluripotency states. However, the major limitation of this study is the absence of a MiPSC-derived cardiomyocytes. Because this study investigated the effect of stem cell engraftment and myocardial viability on the restorative potential of distinct cell types, the MiPSCs, which represent the highest pluripotency state, were selected to demonstrate myocardial salvage. Studies are underway to purify MiPSC-derived cardiomyocytes to assess the restorative potential of the differentiated cardiac cells when compared with the MiPSCs and their engraftment in an immunocompetent mice model. The teratoma formation by the MiPSCs is a clear contraindication to clinical use. However, additional experiments to understand the paracrine mechanism of the cell products derived from the MiPSCs are planned. The exosomes and their associated miRNAs will be identified to elucidate the underlying biological pathway.
in the production of the cytokines involved in myocardial salvage. The functional effects of the cytokines, their corresponding recombinant human analogs and small interfering RNAs, and the exosomes will be studied in preclinical animal models. If significant restoration is confirmed by these MiPSC derivatives, a potential clinical application of the MiPSCs may be to generate these cell products in vitro.

In summary, the MiPSC-treated mice had sustained improvement in myocardial viability and LVEF compared with the uAMCs, c+AMCs, and control groups. These findings were coupled with sustained engraftment of MiPSCs, which enhanced the paracrine effects to salvage the injured myocardium. In contrast, the relatively modest improvements of the uAMC and c-AMC groups were attributed to limited engraftment and the subsequent attenuated release of paracrine factors, providing only transient enhancement of myocardial viability.

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Disclosures

None.

References


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**Novelty and Significance**

**What Is Known?**
- The mechanism of functional restoration with stem cell therapy remains poorly understood.
- The pluripotency states of the stem cell are thought to directly correlate with myocardial restoration potential after acute myocardial injury.
- Novel multimodality imaging using manganese- and delayed-enhanced MRI and bioluminescence imaging allows for serial in vivo evaluations of myocardial function and viability in relation to stem cell engraftment.

**What New Information Does This Article Contribute?**
- Amniotic stem cell–derived induced pluripotent stem cells demonstrated increased production of paracrine factors without evidence for cardiac or endothelial differentiation, consistent with myocardial salvage.
- Amniotic mesenchymal stem cell–derived induced pluripotent stem cell demonstrated significantly greater increase in myocardial function and viability compared with the nonreprogrammed native populations of lesser cell potency.
- Improved myocardial function and viability correlated with the degree of stem cell engraftment.

The underlying myocardial biology of functional restoration by stem cell therapy has been described as either regeneration or salvage of the injured myocardium. Using novel multimodality imaging with manganese-enhanced MRI, delayed-enhanced MRI and bioluminescence imaging, we demonstrate that amniotic stem cell–derived induced pluripotent stem cells–treated mice have a significant and sustained improvement in myocardial function and viability that are not seen in other amniotic stem cell–derived subpopulations of lesser cell potency. This correlated with the degree of stem cell engraftment by bioluminescence imaging. Further analyses demonstrated increased production of paracrine factors without evidence for cardiac or endothelial differentiation, consistent with myocardial salvage.
Direct Evaluation of Myocardial Viability and Stem Cell Engraftment Demonstrates Salvage of the Injured Myocardium
Paul J. Kim, Morteza Mahmoudi, Xiaohu Ge, Yuka Matsuura, Ildiko Toma, Scott Metzler, Nigel G. Kooreman, John Ramunas, Colin Holbrook, Michael V. McConnell, Helen Blau, Phillip Harnish, Eric Rulifson and Phillip C. Yang

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Detailed Methods

Isolation of AMCs from Human Placentas.

A human placenta was obtained from one healthy subject, who provided a written informed consent, at the Stanford University Medical Center. The placenta was placed in HBSS media (Invitrogen, NY, USA) under sterile conditions. The human amniotic membrane from the placenta was separated from the chorion layer and then immediately washed 3 to 5 times with 0.9% NaCl solution to remove blood and mucus. The membrane was cut into 2 x 2 cm pieces and transferred into an enzymatic digestion buffer containing trypsin-EDTA (Invitrogen) in phosphate-buffered saline and incubated at 37°C for 30 minutes. The digested tissue was centrifuged and the supernatant was discarded. Then, the tissue was subjected to a second enzymatic digestion in 50 ml of HBSS containing 50 mg type I collagenase (Invitrogen), 0.01% papain (Sigma, MO, USA) and 10% fetal bovine serum (Invitrogen) for 2 hours at 37°C. After digestion, cells were washed 3 to 5 times and were collected by centrifugation at 200g for 5 minutes. We called this heterogeneous population cells uAMCs.

Fluorescent Activated Cell Sorting.

The uAMCs underwent 2-step FACS on a Vantage Flow Cytometry system (BD Biosciences, CA, USA). Antibodies against the following antigens were used to sort the stem cell population: ckit and SSEA-4 (Biolegend, CA, USA). Sorted cells were cultured
in DMEM media (Invitrogen) supplemented with 110mg/L sodium pyruvate (Sigma), 4mM L-Glutamine (Invitrogen), 10% fetal bovine serum, 1% Pen-Strep (Invitrogen) and 10 ng/mL EGF (R&D Systems, MN, USA) at 37°C and 5% CO2. The sorted ckit/SSEA4^+AMCs were labeled as c^+AMCs.

**BLI Reporter Gene Virus Generation.**

A BLI reporter gene plasmid DNA (courtesy of Joseph Wu, Stanford University\(^1\)) was isolated using the plasmid Maxi-kit (Qiagen Inc., CA, USA). 293FT cells were plated at a density of 5x10^6 cells in 15 cm dish and grown in DMEM with 10% fetal bovine serum overnight, prior to transfection. All transfections were carried out using Fugene (Roche, Germany) according to the manufacturer's instructions. A total of 37 µg of BLI-reporter gene plasmid and 25 µg of pDM2G with 37.5 µg of PAX2 were used for each transfection. Approximately 48 hours after transfection, the supernatant was collected and centrifuged at 64000g for 2 hours. The pellets were suspended in 500 µL DMEM (Invitrogen) and used for transduction.

**Virus Production and iPSC (MiPSC) Generation**

The plasmid of pHAGE2EF1-OKSM (courtesy of G. Mostoslavsky, Boston University) was employed to generate the virus\(^2\). The 293FT cells were transfected at 90% confluence using lipofectamine (Invitrogen). For a 10 cm plate, 1 mL OptiMEM (Invitrogen), 36 µL lipofectamine, and 24 µg DNA mixture (20:1:1:1:2; pHAGE2: tat: rev: gag/pol: vsv-g) were used. Virus was harvested over 3 days and concentrated by spinning for 1.5 hours at 16,500 RPM at 4°C. Approximately 100,000 AMCs were
seeded using a 6-well plate and infected with 150 µL of concentrated virus in the presence of 10 µg/mL polybrene. The medium was replaced after 24 hours with DMEM supplemented with 20% fetal bovine serum and changed every 2 days. On day 6 post-infection, the cells were trypsinized (trypLE; Invitrogen), passaged at a 1:6 ratio, and cultured onto one 6-well plate pre-seeded with irradiated mouse fibroblasts (MEF-irr; GlobalStem, MD, USA) on a feeder layer of 0.2% gelatin (Sigma). The cells were grown until spontaneous colony formation using hESC culture media containing knockout DMEM with 20% knockout serum (Invitrogen), 1 mM of L-glutamine (Invitrogen), 0.1 mM 2-mercaptoethanol (Millipore, MA, USA), 1% non-essential amino acid solution (Invitrogen), and 10 ng/mL of bFGF (R&D Systems).

In Vivo Magnetic Resonance Imaging.

3T CMR (Signa 3T HDx, General Electric Medical Systems, WI, USA) was performed using a dedicated mouse coil (Rapid MR International, Germany). Mice were serially imaged by CMR at weeks 1, 2 and 4 after LAD ligation and treatment. Mice were maintained under anesthesia by inhaled isoflurane (1-2%). Electrocardiographic gating was obtained with two subcutaneous precordial leads and body temperature was monitored with a rectal probe during the entire scan (SA Instruments, Inc, NY, USA). Left ventricular function was evaluated with electrocardiographically triggered cine sequence (TE 6 ms, TR 16.4 ms, FA 45°, field of view (FOV) 7 cm², matrix 256x256, slice gap 0 mm, slice thickness 1.0 mm, 2 excitations, and 20 cardiac phases). MEMRI was performed using fast gradient echo inversion recovery (fGRE-IR) sequence with FOV 4cm, slice thickness 1mm, matrix 256x256, TE 3.4ms, FA 45°, 2R-R acquisition, TI
300-500ms, and NEX2 with IP injection of 0.7 cc/kg of manganese solution (EVP1001-1, Eagle Vision Pharmaceutical Corp, PA, USA) prior to MEMRI acquisition. DEMRI was performed 24 hours later with IP injection of 0.2 mmol/kg gadopentetate dimeglumine (Magnevist, Berlex Laboratories, MA, USA) using a similar fGRE-IR sequence but with a TI of 200-300ms. The images were analyzed offline using Osirix (Pixmeo, Switzerland) with manual contouring of LV mass and scar volume tracing. Tracings of MEMRI enhancement, MEMRI defect, and DEMRI enhancement were generated for each short-axis slice and integrated to determine viable myocardial and scar volumes in matched murine hearts. Peri-infarct region was defined as the region of overlap between DEMRI enhancement and MEMRI defect, representing the area of viable myocardium (MEMRI) in the region of non-viable myocardial scar (DEMRI), as shown previously. Percent MEMRI scar volume = (MEMRI defect volume x 100)/total LV mass volume; % MEMRI viable myocardial volume = (MEMRI enhancement volume x 100)/total LV mass volume; % DEMRI scar volume = (DEMRI scar volume x 100)/total LV mass volume; % DEMRI-MEMRI peri-infarct volume = (DEMRI-MEMRI peri-infarct volume x 100)/total LV mass volume.

**Immunohistology.**

Hearts were flushed with normal saline solution and subsequently placed in 4% paraformaldehyde for 24 hours at room temperature, followed by 24 hours in 70% ethanol at room temperature. The hearts were then embedded in paraffin blocks and sectioned in 4 µm slices. The slides were then stained with hematoxylin and eosin.
Unstained paraffin embedded myocardium slides were deparaffinized using 2 washes of 5 minutes each in Histoclear II (EMS Diasum, PA, USA) followed by an ethanol rehydration series of 100%, 90%, 75%, and 50% EtOH for 3 minutes each. Antigen unmasking was then performed in 10mM sodium citrate pH 6.0 in a water bath set to 98°C for 20 minutes. After the slides were rinsed in tap water, a paraffin pen was used to encircle the sections and rinsed for 15 minutes in PBS + 1% BSA+0.1% Triton-X 100+0.01M Glycine (Sigma). Sections were then rinsed in PBS + 1% BSA for 5 minutes followed by blocking of the sections for 30 minutes in PBS + 1% BSA + 5% Normal Goat Serum (Sigma). MiPSCs and c^+AMCs of human origin were detected in murine myocardium utilizing primary antibodies specific for human mitochondria. Sections were incubated in 1:50 mouse anti-human mitochondria (MCH, MAB1273, Millipore) overnight at 4°C and visualized with a 1:200 concentration of Goat anti-Mouse IgG1 AlexaFluor 488 secondary antibody (Life Technologies), incubated for 2 hours in the dark at room temperature. Primary antibodies specific for cardiomyocytes (cardiac Troponin T, MS-295, 1:400, ThermoFisher, MA, USA) and endothelial cells (anti-CD31, 1:100, BD Biosciences) were also detected using a Goat Anti-Mouse IgG1 AlexaFluor 488 Ab at a 1:200 concentration. A rabbit polyclonal antibody to ckit was used (ckit H-300, sc-5535, 1:100, Santa Cruz Biotechnology, CA, USA) and visualized with Goat Anti-Rabbit IgG AlexaFluor 488 (1:200). The cellular cytoskeleton was counterstained for 20 minutes with AlexaFluor 568 Phalloidin (1:40, Life Technologies, CA, USA) to visualize F-actin. Slides were then mounted and nuclei were detected in Vectashield Hard Set with DAPI (Vector Labs, CA, USA). Finally, luciferin was immunostained using 4% PFA-PBS fixation of the frozen section. Sections were incubated overnight at 4°C in
rabbit anti-firefly luciferase (1:200, Abcam, MA, USA) and anti-human nuclear antigen (1:100, Millipore) and visualized with anti-rabbit AlexaFluor 488 (Jackson ImmunoResearch, PA, USA) and anti-mouse Cy3 (Jackson ImmunoResearch) secondary antibodies.

References: