Intracoronary Delivery of Autologous Cardiac Stem Cells Improves Cardiac Function in a Porcine Model of Chronic Ischemic Cardiomyopathy

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Methods and Results—Pigs underwent a 90-minute coronary occlusion followed by reperfusion. Three months later, autologous CSCs (n=11) or vehicle (n=10) were infused into the infarct-related artery. At this time, all indices of left ventricular (LV) function were similar in control and CSC-treated pigs, indicating that the damage inflicted by the infarct in the 2 groups was similar; 1 month later, however, CSC-treated pigs exhibited significantly greater LV ejection fraction (echocardiography) (51.7±2.0% versus 42.9±2.3%, P<0.01), systolic thickening fraction in the infarcted LV wall, and maximum LV dP/dt, as well as lower LV end-diastolic pressure. Confocal microscopy showed clusters of small αsarcomeric actin–positive cells expressing Ki67 in the scar of treated pigs, consistent with cardiac regeneration. The origin of these cycling myocytes from the injected cells was confirmed in 4 pigs that received enhanced green fluorescent protein–labeled CSCs, which were positive for the cardiac markers troponin I, troponin T, myosin heavy chain, and connexin-43. Some engrafted CSCs also formed vascular structures and expressed α-smooth muscle actin.

Conclusions—Intracoronary infusion of autologous CSCs improves regional and global LV function and promotes cardiac and vascular regeneration in pigs with old myocardial infarction (scar). The results mimic those recently reported in humans (Stem Cell Infusion in Patients with Ischemic Cardiomyopathy [SCIPIO] trial) and establish this porcine model of ischemic cardiomyopathy as a useful and clinically relevant model for studying CSCs. (Circulation. 2013;128:122-131.)

Key Words: angiogenesis inducers • heart failure • myocardial infarction • muscle development • stem cells

Over the past decade, numerous animal studies and clinical trials have established the ability of various stem cell populations to improve cardiac function and attenuate left ventricular (LV) remodeling in heart failure. Among the cells tested, resident cardiac stem cells (CSCs) appear particularly promising. Based on the expression of the surface receptor tyrosine kinase c-kit, in 2003, Beltrami et al12 isolated a distinct population of resident CSCs (c-kit+ CSCs) in adult rat hearts that are self-renewing, clonogenic, and multipotent, ie, they differentiate into all 3 major cardiac lineages (myocytes, vascular smooth muscle cells, and endothelial cells).5,12-15 The practical utility of c-kit+ CSCs is supported by the fact that these cells can be isolated from small fragments of cardiac tissue and expanded for subsequent autologous administration.4,12,16

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Prior work in our laboratory using autologous or syngeneic c-kit+ CSCs has shown that transplantation of these cells attenuates LV remodeling and improves LV function in the settings of both acute and chronic myocardial infarction (MI) in rodents.4,5,12-15 We have recently obtained similar results in SCIPIO (Stem Cell Infusion in Patients with Ischemic Cardiomyopathy; NCT00474461), the first clinical trial of CSCs.10 SCIPIO is a phase I, open-label, randomized study designed to investigate the safety and feasibility of autologous CSCs.
CSC infusion in patients with severe heart failure resulting from ischemic heart disease. However, despite these encouraging results, many questions pertaining to the therapeutic efficacy of CSCs remain unanswered (eg, what is the optimal time for CSC administration? Is the intracoronary route the optimal modality of administration? What is the optimal protocol for intracoronary infusion?). Many of these questions cannot be realistically or safely examined in clinical trials, nor can they be addressed in a rodent model where cell delivery with an intracoronary catheter (similar to the human procedure) is impossible. Answering these important questions will require the use of large and clinically relevant animal models.

Accordingly, the goal of the present investigation was to develop a porcine model of chronic ischemic cardiomyopathy caused by an old MI (scar) and to determine whether intracoronary delivery of autologous CSCs (similar to the protocol used in the SCIPIO trial) recapitulates the results obtained clinically in SCIPIO.

Methods

This study was performed in accordance with the guidelines of the Animal Care and Use Committee of the University of Louisville (KY) School of Medicine and following the guidelines set forth by the 1996 Guide for the Care and Use of Laboratory Animals. The experimental protocol of the study is illustrated in Figure 1.

Induction of Myocardial Infarction and Tissue Harvest

Male Yorkshire pigs (13.5±0.8 kg, age 8–10 weeks) were anesthetized, and the heart was exposed by a median sternotomy. The right atrial appendage was cross-clamped and the tip (1–2 g) resected for isolation of CSCs. The harvested atrial samples were rinsed in phosphate-buffered saline, cut into small (1–2 mg) pieces, and snap frozen in a freezing medium composed of the growth culture medium premixed with dimethyl sulfoxide (9:1 vol/vol). The growth medium consisted of Ham F12 (BioWhittaker), 10% fetal bovine serum (Gibco), and penicillin/streptomycin (BioWhittaker). balloon catheter (Boston Scientific) was advanced over a guide wire (BMW, Abbott Vascular) and positioned at the level of the mid left anterior descending coronary artery. A 2-minute balloon inflation was performed once to verify cessation of coronary flow distal to the balloon catheter (with the use of contrast medium injection) and to increase microvascular permeability. A sequence of three 3-minute balloon inflations (4–6 atmospheres) interspersed with 3-minute deflation periods was then performed. The CSC solution (500,000 cells in 5 mL of sterile Plasma-Lyte A solution, divided into 3 injections) or vehicle (5 mL of sterile Plasma-Lyte A solution) was injected manually at a constant rate through the central port of the angioplasty balloon catheter during the 3-minute balloon inflation time.

Blood samples for serial measurement of cardiac markers were obtained before and at serial times after catheterization. Details are provided in the online-only Data Supplement. Pigs were followed for 31±1 days after intracoronary vehicle or CSC delivery. Aspirin (325 mg/d) was administered orally starting 2 days before catheterization; and MI, myocardial infarction.

Isolation and Culture of CSCs

The frozen atrial specimens were thawed, cut into thinner slices, and plated on uncoated dishes containing growth medium. One week after tissue seeding, outgrowth of CSCs was apparent and documented by microscopic examination. After an additional week, a cluster of ≈5000 cells surrounded each tissue fragment. The growth medium was removed and cells were detached with 3 to 4 mL of 0.25% trypsin (Sigma) per dish. Cells were sorted for c-kit with Miltenyi immunomagnetic beads (Miltenyi Biotech), and c-kit+ cells were plated in growth medium for expansion. The characteristics of c-kit+ cells were analyzed using antibodies against c-kit and against markers of cardiac lineage or vascular commitment (GATA-4, MEF2C, α-sarcromeric actin, myosin heavy chain, von Willebrand factor, and smooth muscle actin).

In preparation for the infusion, CSCs were transferred to a vial filled with growth medium. The final autologous CSC product was prepared by centrifuging the cells at 400g. The supernatant was removed and the cellular pellet resuspended in sterile Plasma-Lyte A solution. BSL indicates baseline; Cath, at the time of catheterization; CSC, cardiac stem cell; echo, echocardiogram; and MI, myocardial infarction.

![Figure 1. Experimental protocol. Three groups of pigs were studied (groups I–III). Four days after a baseline echocardiogram, pigs underwent a 90-minute coronary occlusion followed by reperfusion or sham surgery. At 3 to 4 months after MI (97±12 days in vehicle-treated and 96±6 days in CSC-treated groups), pigs received intracoronary infusion of vehicle (group II), or autologous CSCs into the infarct-related artery by the use of a balloon catheter (group III). Group I served as noninfarcted controls. Echocardiographic and hemodynamic assessment of cardiac function was performed before treatment and at the time of euthanasia. At 31 days after vehicle/CSC therapy, pigs were euthanized for morphometric and histological studies. BSL indicates baseline; Cath, at the time of catheterization; CSC, cardiac stem cell; echo, echocardiogram; and MI, myocardial infarction.](http://circ.ahajournals.org/doi/abs/10.1161/CIRCULATIONAHA.117.028410?journalCode=circ)
Echocardiographic and Hemodynamic Studies

Echocardiograms and hemodynamic measurements were obtained at baseline (before CSC delivery) and 31 days after CSC delivery (just before euthanasia). A detailed description is provided in the online-only Data Supplement.

Morphometry and Histology

At the completion of the echocardiographic and hemodynamic measurements, the thorax was reopened. Pigs received an intravenous bolus of heparin (100 IU/kg) followed by an intravenous bolus of CdCl₂ (100 mmol/L) and KCl (1 mol/L) to arrest the heart in diastole. The aortic root was perfused with 10% buffered formalin at a pressure adjusted to match the mean arterial pressure. The perfused fixed heart was weighed and cut into serial slices perpendicular to its longitudinal axis and the slices were embedded in paraffin. Samples were harvested also from brain, lung, liver, spleen, and kidney and kept in formalin.

Immunohistochemistry was performed on formalin-fixed 4-µm-thick sections by using various antibodies. CSCs were identified with the c-kit antibody; myocytes with α-sarcomeric actin, troponin I, troponin T (TnT), cardiac myosin heavy chain, and connexin-43 antibodies; and smooth muscle cells with α-smooth muscle actin antibodies. Scar tissue was detected with a mixture of collagen type III and type I antibodies. Cycling cells were detected with Ki67 antibodies. Colocalization of cell-specific markers with enhanced green fluorescent protein (EGFP) was used to identify cells that originated from CSCs. Nuclei were identified with propidium iodide.12,14,18,19

Statistical Analysis

Data are reported as mean±standard error of the mean. Comparisons of serial measurements in 2 or 3 groups were performed with 2-way repeated measures analysis of variance (time and group). Posttreatment LV end-diastolic pressure (and dP/dt max) were compared by using analysis of covariance to take into account the pretreatment values. Post-versus pretreatment and vehicle versus CSC-treated comparisons were performed by using paired and unpaired Student t tests, respectively, with the Bonferroni correction in which the correction factor was the number of comparisons made for each variable. The statistical software packages used were SigmaStat 2.0 for Windows and R (http://www.r-project.org/). Probability values of <0.05 were considered statistically significant.

Results

Exclusions

A total of 34 pigs were used in this study (5 nonoperated and 29 infarcted pigs). Of the 29 pigs subjected to MI, 8 were excluded before treatment (7 pigs died [1 owing to ventricular fibrillation during left anterior descending coronary artery occlusion, 4 owing to ventricular fibrillation within 24 hours after reperfusion, 1 at 2 months after infarction, and 1 during cardiac catheterization] and 1 pig was excluded because of a complication unrelated to CSCs [bladder extrusion]). Of the remaining 21 pigs, 10 were assigned to the vehicle-treated group and 11 to the CSC-treated group. Among these, 11 pigs (5 control and 6 CSC-treated) developed ventricular fibrillation during left anterior descending coronary artery occlusion or within 2 hours of reperfusion and were successfully cardioverted by internal defibrillation (5–20 joules).

General Characteristics

The interval from MI to treatment (intracoronary infusion of vehicle or CSCs) was 97±12 days in vehicle-treated and 96±6 days in CSC-treated pigs. There was no significant intragroup difference in heart rate, mean arterial pressure, serum electrolytes, or hemoglobin levels between the vehicle- and the CSC-treated groups during surgery or after cardiac catheterization (Table I in the online-only Data Supplement). Arterial blood gases were within normal limits in both groups (data not shown). Body weight was similar among the 3 groups throughout the protocol (Table I in the online-only Data Supplement).

Cardiac Enzymes

Before intracoronary infusion, creatine kinase and lactate dehydrogenase levels (which are nonspecific markers of muscle injury) were elevated to a similar extent in vehicle-treated and CSC-treated pigs (Table I), likely as a result of the neck dissection required for carotid arterial access; however, in the subset of pigs in which they were measured, TnT and creatine kinase MB fraction levels (specific markers of myocardial injury) were normal (Figure 2). After balloon inflation, lactate dehydrogenase, total creatine kinase, and myoglobin continued to rise and peaked at 6 to 12 hours after the procedure (Table I), probably a delayed result of the neck dissection; in contrast, TnT and creatine kinase MB fraction levels exhibited minimal or no elevation (Figure 2). Importantly, neither peak nor cumulative enzyme levels differed significantly between vehicle-treated and CSC-treated groups (Table I and Figure 2), indicating that CSC delivery was not associated with more frequent or more extensive myocardial injury.

Hemodynamic Data

As shown in Table I and Figure 3A and 3B, at the time of catheterization (before intracoronary infusion of vehicle or CSCs), there was no significant difference between vehicle- and CSC-treated groups with respect to heart rate, left ventricular (LV) systolic pressure, LV end-diastolic pressure, LV dP/dt max, or LV dP/dt min (all variables were measured with a Millar catheter). In both groups, heart rate increased significantly at the 31-day follow-up (from 80.3±3.6 to 87.7±4.1 bpm

| Table 1. Cardiac Enzymes During and After Cardiac Catheterization |
|------------------|------------------|------------------|------------------|
|                  | Before Intracoronary Infusion | Peak Levels After Catheterization | Cumulative Levels >48 h Postcatheterization |
| Vehicle-treated (n=10) |                  |                  |                  |
| LDH, U/L          | 798±83            | 4506±1473*       | 50 958±10 273  |
| CK, U/L           | 844±256           | 10 241±2769*     | 129 659±40 278  |
| TnT, ng/mL        | 0.009±0.001       | 0.034±0.018      | 1.584±1.106     |
| CK-MB, ng/mL      | 0.37±0.04         | 0.30±0.04        | 8.51±2.18       |
| CSC-treated (n=11) |                  |                  |                  |
| LDH, U/L          | 865±102           | 4730±1241*       | 53 441±13 284  |
| CK, U/L           | 925±278           | 1467±6462*       | 162 734±59 527  |
| TnT, ng/mL        | 0.010±0.000       | 0.044±0.026      | 0.944±0.521     |
| CK-MB, ng/mL      | 0.40±0.04         | 0.34±0.04        | 5.83±0.76       |

Values are means±SEM. CK indicates creatine kinase; CK-MB, creatine kinase MB fraction; CSC, cardiac stem cell; LDH, lactate dehydrogenase; SEM, standard error of the mean; and TnT, troponin T.

*P<0.05 vs preinfusion value (paired t test).
in vehicle-treated group and from 82.6±4.2 to 89.4±2.9 bpm in the CSC-treated group, P<0.05 in both). In vehicle-treated pigs, LV systolic pressure, LV end-diastolic pressure, LV dP/dt_{max}, and LV dP/dt_{min} did not change significantly. In contrast, in CSC-treated pigs, the LV end-diastolic pressure decreased (from 15.9±0.8 mm Hg at catheterization to 11.8±1.0 mm Hg at the 31-day follow-up, P<0.05) and the LV dP/dt_{min} increased (from 967±91 mm Hg/s at catheterization to 1251±74 mm Hg/s at the 31-day follow-up, P<0.05) (Table 2, Figure 3A and 3B).

Echocardiographic Data
Before cardiac catheterization, echocardiographic parameters of LV structure and function were similar in vehicle-treated and CSC-treated infarcted pigs (although they differed from noninfarcted control animals) (Table 3, Figure 3C through 3F). At 31 days of follow-up, these variables had not changed significantly in noninfarcted control animals (Table 3, Figure 3C through 3F). In vehicle-treated pigs, the LV end-diastolic diameter and volume (calculated by the Teichholz formula) increased by 11.3±8.1% and 38.7±24.3%, respectively, over the ensuing 31 days, but the differences did not reach statistical significance (Table 3). In contrast, these variables remained virtually unchanged in CSC-treated pigs (Table 3). During the 31 days following vehicle infusion, the diastolic thickness of the infarcted LV wall (as assessed by M-mode echocardiography) decreased by 0.57±0.49 mm (5.5±4.9%) in control animals but increased by 1.55±0.64 mm (21.8±9.0% [P=0.029]) in CSC-treated animals (Table 3).

At the time of treatment, the systolic thickening fraction in the infarcted wall was depressed to a similar extent in the 2 groups (Table 3, Figure 3E). In vehicle-treated pigs, this variable did not change over the ensuing 31 days, whereas in CSC-treated pigs, it increased from 22.7±2.5% to 32.7±2.7% (P<0.05 versus precatheterization values in CSC-treated pigs and P<0.05 versus final values in vehicle-treated pigs) (Table 3, Figure 3E), indicating improved regional systolic function. In the noninfarcted LV wall, neither the diastolic thickness nor the systolic thickening fraction changed appreciably over time, and neither variable exhibited a significant difference between the 2 groups (Table 3).

LV fractional shortening and ejection fraction were similarly depressed in the 2 groups at the time of treatment; these variables did not change in vehicle-treated pigs but increased significantly in CSC-treated animals (Table 3, Figure 3F). In vehicle-treated pigs, the ejection fraction was 45.6±2.5% at catheterization and 42.9±2.3% 31 days later, whereas in CSC-treated pigs it increased from 45.4±2.0% to 51.7±2.0% (P<0.05 versus precatheterization values in CSC-treated pigs and P<0.01 versus final values in vehicle-treated pigs, Figure 3F), indicating improved global LV systolic function.

Gross Pathology and Histopathology of the Heart
As expected, gross inspection of the heart revealed the presence of scars in the anteroseptal and anterior LV walls (Figures 4 and 5). Histological and immunohistochemical examination of the heart showed the presence of confluent areas of collagen accumulation in the scarred areas. In treated pigs, islands of viable myocardium were observed within the scar (Figure 5). At higher magnification, these consisted of clusters of small (average cross-sectional area, ≈50 µm²) fetal-neonatal–like myocytes, as identified by the presence of α-sarcomeric actin. These cells were absent in vehicle-treated hearts, and some of them expressed Ki67 in the nucleus (2.36±0.84% of the infarcted area, n=5) (Figure 6), suggesting that at 4 months after infarction, these CSC-derived myocytes had not reached terminal differentiation and growth arrest but rather possessed a residual capacity to divide. The percentage of Ki67-positive nuclei in the remote region with no infarction (posterolateral LV wall) was similar in the 2 groups (0.17±0.08% in controls [n=8] versus 0.19±0.06% in the treated pigs [n=6]). More mature, dispersed cardiomyocytes were also detected in a scattered

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**Table 2. Hemodynamic Data Before Treatment and Before Euthanasia**

<table>
<thead>
<tr>
<th></th>
<th>Vehicle-Treated (n=10)</th>
<th>CSC-Treated (n=11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart rate, bpm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Before treatment</td>
<td>80±4</td>
<td>83±4</td>
</tr>
<tr>
<td>31-day follow-up</td>
<td>88±4*</td>
<td>89±3*</td>
</tr>
<tr>
<td>LVSP, mm Hg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Before treatment</td>
<td>85±6</td>
<td>82±4</td>
</tr>
<tr>
<td>31-day follow-up</td>
<td>82±4</td>
<td>83±2</td>
</tr>
<tr>
<td>dP/dt_{max}, mm Hg/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Before treatment</td>
<td>−1328±95</td>
<td>−1375±101</td>
</tr>
<tr>
<td>31-day follow-up</td>
<td>−1233±116</td>
<td>−1388±97</td>
</tr>
</tbody>
</table>

Values are means±SEM. CSC indicates cardiac stem cell; and LVSP, left ventricular systolic pressure.

*P<0.05 vs before treatment (paired t test).
Figure 3. Assessment of LV function before and after vehicle or CSC therapy: hemodynamic variables (LV end-diastolic pressure [A] and LV \( dP/dt_{\text{max}} \) [B]), representative M-mode echocardiographic images at 30 days after treatment in pigs that were given vehicle (C) and CSCs (D), and quantitative echocardiographic analysis of LV function (infarct wall thickening fraction and ejection fraction) (E and F). In comparison with the vehicle-treated pig, the CSC-treated animal exhibited a smaller LV cavity, a thicker infarcted wall, and improved motion of the infarcted wall (C and D). Quantitative echocardiographic analysis shows improvement in LV functional parameters at 30 days after CSC treatment (E and F). Data are means±SEM. * \( P<0.05 \) vs noninfarcted controls; § \( P<0.05 \) vs vehicle-treated pigs (unpaired \( t \) test). Cath indicates at the time of catheterization; CSC, cardiac stem cell; LV, left ventricular; and LVEDP, LV end-diastolic pressure.
IWTd, mm

Before Cath 9.84±0.34 9.75±0.43 8.50±0.42
Final 9.48±0.73 9.19±0.57 10.05±0.38*

IWTs, mm

Before Cath 15.22±0.79 12.15±0.65 10.47±0.59
Final 15.28±1.04 11.01±0.66 13.28±0.43*

PWThF, %

Before Cath 10.69±0.59 10.20±0.54 10.07±0.55
Final 10.41±0.71 9.57±0.39 10.56±0.52

PWTh, mm

Before Cath 15.20±1.16 14.03±0.83 13.83±0.67
Final 15.18±1.04 13.69±0.74 14.88±0.56

LVEDD, mm

Before Cath 33.44±2.13 34.78±1.63 35.42±1.56
Final 36.53±1.68 38.06±2.36 35.73±1.45

LVESD, mm

Before Cath 11.01±0.66 12.15±0.65 10.47±0.59
Final 11.05±0.71 10.83±0.42 10.05±0.38*

FS, %

Before Cath 21.34±1.55 25.63±1.49 25.63±1.31
Final 20.23±1.55 28.76±2.11 24.90±1.38

FAc, %

Before Cath 36.24±2.12 26.50±1.75 27.15±1.53
Final 44.44±2.77 24.73±1.51 30.68±1.47*

EDV, mL

Before Cath 46.74±7.23 51.66±5.26 53.92±5.53
Final 50.67±2.17 65.16±9.61 54.72±5.38

Histopathologic Examination of Other Organs

There was no gross evidence of tumors or organ damage in the liver, lung, spleen, kidney, and brain of CSC-treated animals (data not shown). Detailed qualitative histopathologic analysis of tissue sections from these organs showed no differences between the 2 groups, and specifically no macro- or micro-infaracts, tumors, or increased inflammation in CSC-treated in comparison with vehicle-treated pigs. Furthermore, the number of c-kit+ cells in the lungs was not significantly different between vehicle-treated (120±16 cells/mm² [n=4]) and CSC-treated groups (85±14 cells/mm² [n=6], P=not significant). Thus, there was no evidence of systemic complications following intracoronary infusion of CSCs.

Discussion

We have previously demonstrated in rats that administration of autologous c-kit+ CSCs is effective in regenerating cardiac tissue and alleviating postinfarction LV remodeling and dysfunction when these cells are infused via the intracoronary route in the setting of an old MI. More recently, we have performed the first clinical trial of CSCs (SCIPIO), in which we found that intracoronary infusion of autologous CSCs improves LV function, quality of life, and New York Heart Association functional class, reduces scar size, and increases viable myocardium in patients with ischemic cardiomyopathy. However, many questions regarding the optimal use of CSCs remain to be addressed. Answers to these questions will require the use of a large, clinically relevant animal model to study intracoronary infusion of c-kit+ cells in the setting of scarred myocardium (in which the expression of growth factors and adhesion molecules is markedly diminished or even absent). The present study was undertaken to fill this gap and develop such a model. We used a transient coronary occlusion followed by reperfusion (as opposed to a permanent coronary occlusion) because, in current practice, most patients with acute MI receive reperfusion therapy. A model fashion within the scar; these myocytes were both mononucleated and binucleated.

To investigate the origin of the myocytes observed in the scar, 4 pigs received EGFP-labeled CSCs. In these animals, EGFP-positive cells (0.42±0.09%, n=4) were observed in the infarcted region (Figure 7). The coexpression of a-sarcomeric actin, troponin I (Figure 8A), TnT (Figure 8B), and myosin heavy chain (Figure 8C) in these cells indicates that they were newly formed myocytes derived from the autologous CSCs. Newly formed myocytes expressed connexin-43 (Figure 8D) suggesting functional integration with adjacent myocytes. EGFP-positive small arterioles (green vessel density, 132±12/mm²) and capillaries (green vessel density, 59.9±8.9/mm²) were also observed in the scarred region, suggesting vascular regeneration (Figure 8E).
of a 3-month-old reperfused MI was selected because, by this time, the acute inflammatory response in the pig has resolved and the formation of the scar is complete, a setting analogous to that of patients with chronic ischemic cardiomyopathy.

The salient results of the present study can be summarized as follows: (1) in this porcine model of chronic ischemic cardiomyopathy, intracoronary infusion of $5 \times 10^5$ autologous CSCs is well tolerated, with no rise in cardiac enzymes or evidence of microembolization; (2) intracoronary infusion of $5 \times 10^5$ CSCs results in an improvement in both regional function in the infarcted region and global LV function, as demonstrated by 2 independent methods (echocardiography and hemodynamic studies), and in attenuation of LV wall thinning in the infarcted region, as well; (3) these salubrious effects are associated with the formation of new cardiomyocytes and vascular structures that are derived from transplanted cells. To our knowledge, this is the first time that CSCs have been isolated and used for therapeutic studies in a porcine model. The clinical relevance of these preclinical observations is underscored by the fact that the beneficial effects of CSCs were observed in the setting of transient ischemia followed by reperfusion, which is relevant to the majority of patients with MI, and by the use of a route of CSC administration (intracoronary infusion) that is easily applicable to patients and has already been used clinically in the SCIPIO trial. Thus, this porcine model should be useful to further study the utility of CSCs in treating ischemic cardiomyopathy. Taken together, the present results demonstrate that transplantation of CSCs exerts important salutary effects on post-MI LV dysfunction even after the healing process is completed.

Potential Mechanisms

In CSC-treated pigs, the infarcted region was thicker and exhibited greater wall thickening than in controls (Table 3 and Figure 3E), which may reflect the increased content of viable myocardium consisting mainly of small myocytes (Figure 5). To determine whether the small myocytes that we observed (Figures 6 through 8) represented dividing amplifying cells, we evaluated Ki67, a nuclear protein that is expressed in cycling cells in late G1, S, G2, and early mitosis. Positivity for Ki67+ myocytes in the infarcted region, as well; (3) these salubrious effects are associated with the formation of new cardiomyocytes and vascular structures that are derived from transplanted cells. To our knowledge, this is the first time that CSCs have been isolated and used for therapeutic studies in a porcine model. The clinical relevance of these preclinical observations is underscored by the fact that the beneficial effects of CSCs were observed in the setting of transient ischemia followed by reperfusion, which is relevant to the majority of patients with MI, and by the use of a route of CSC administration (intracoronary infusion) that is easily applicable to patients and has already been used clinically in the SCIPIO trial. Thus, this porcine model should be useful to further study the utility of CSCs in treating ischemic cardiomyopathy. Taken together, the present results demonstrate that transplantation of CSCs exerts important salutary effects on post-MI LV dysfunction even after the healing process is completed.

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them with EGFP and assessing proteins specific for myocytes and smooth muscle cells. We found EGFP+ cells that expressed the cardiac-specific markers α-sarcomeric actin, troponin I, TnT, and myosin heavy chain (Figures 7 and 8A through 8C), suggesting the differentiation of transplanted cells into cardiac myocytes. Overall, in the infarcted region, all myocytes positive for Kit67 expressed EGFP. To characterize further the properties of these new cells, we determined the expression of connexin-43, and found it to be present at the surface of closely aligned differentiating cells, between new myocytes and preexisting and regenerated myocytes (Figure 8D). This result suggests the onset of functional competence in the regenerating heart muscle. We also found EGFP-expressing cells in the vessel wall; these cells were positive for α-smooth muscle actin, documenting the differentiation of CSCs into smooth muscle cells (Figure 8E). This finding is consistent with previous studies in which transplantation of CSCs into ischemic myocardium induced angiogenesis.22

Taken together, these observations are consistent with the concept that adoptive transfer of CSCs resulted in their proliferation and differentiation into cardiac lineages.

Previous Studies

Prior studies of bone marrow–derived mesenchymal stem cells in pigs have demonstrated an increase in endogenous c-kit+ CSCs23 and the mobilization of c-kit+ bone marrow progenitor cells, as well,24 with improvement in LV function after MI. The only previous study of cardiac-derived cells in a porcine model of chronic ischemic cardiomyopathy was performed with intracoronary infusion of autologous cardiosphere-derived cells (CDCs), produced from endomyocardial biopsy samples, in pigs with a 4-week-old MI.6 The authors claimed that CDC infusion resulted in engraftment, formation of mature cardiac cells, reduction in relative infarct size, and improvement in LV remodeling and hemodynamic function 8 weeks later. The evidence provided in support of these claims, however, was largely inadequate. Early engraftment, myocardial damage, and long-term engraftment were assessed in only 2 pigs for a given dose of CDCs. The only evidence of engraftment provided in that study was 1 photograph (Figure 4) purporting to show a few X-gal+ cardiomyocytes that, however, cannot be clearly recognized as such because of the quality of the image. Infarct (scar) size did not change after CDCs (11.0 g before CDCs versus 10.6 g after CDCs). The concept of a decrease in relative infarct size (ie, infarct size expressed as percent of LV mass) has uncertain significance; in that study,6 it reflected simply an increase in total LV mass (possibly attributable to hypertrophy), not a decrease in scar size. In addition, CDCs produced no significant change in LV end-diastolic or end-systolic volume, LV ejection fraction, or LV end-diastolic pressure.6 Thus, the authors’ conclusion that CDC delivery “results in formation of new cardiac tissue, reduces relative infarct size, and attenuates adverse remodeling” is not supported by the data.

Intracoronary infusion is an attractive method for cell delivery to the heart because it can disseminate cells relatively uniformly to the entire region infused,25 it is widely available clinically, it is less invasive than intramyocardial injection, and it has been used in numerous clinical trials.26-33 Other adult stem cells, such as mesenchymal stem cells34-36 and CDCs,6 have been shown to produce microvascular occlusion after...
intracoronary delivery, raising concern over the use of this approach in patients. This is not surprising, because the diameter of mesenchymal stem cells and CDCs is ≈20 μm, which may exceed the diameter of some resistance arterioles. In contrast, CSCs are ≈10 μm in diameter, providing an advantage over other adult stem cells for intracoronary delivery.

**Study Limitations**

The present study has a number of limitations. First, CSCs were compared with vehicle. We did not examine the effects of a control cell population (ie, a population of nonprogenitor cells). Second, although the improvement in cardiac function and the finding of cardiac-specific markers in K167+ and EGF+ cells suggests regeneration, we did not measure the actual target of regenerative therapy, scar mass and viable myocardial mass, because of the unavailability of MRI. Nevertheless, the functional improvement afforded by CSCs was impressive, and would be clinically significant regardless of regeneration. Moreover, the results were similar to those that we obtained in the SCIPIO trial, supporting the utility of this porcine model. Finally, we wish to emphasize that the present work describes a promising new cell therapy strategy but only begins to explore the mechanisms of benefit. The functional improvement and histological evidence of regeneration in CSC-treated hearts now serve to motivate studies aimed at establishing how much of the observed benefit is attributable to regeneration by exogenous versus endogenous CSCs or to other factors, such as paracrine effects and enhanced angiogenesis.

**Conclusions**

This is the first study to provide evidence that intracoronary infusion of c-kit+ CSCs promotes myocardial and vascular regeneration and improves cardiac function in a large animal model of chronic ischemic cardiomyopathy. This is also the first preclinical study to demonstrate that intracoronary delivery of CSCs exerts beneficial effects even when implemented as late as 3 months after MI, when the infarcted tissue has been replaced by a mature scar. From a clinical perspective, these cells can be isolated from endomyocardial biopsies, expanded, and administered back to patients, avoiding rejection and other complications associated with nonautologous transplantation. The results reported herein provide a clinically relevant model of chronic ischemic cardiomyopathy that should be useful for further investigation of the efficacy and mechanism of action of CSCs.

**Acknowledgments**

We gratefully acknowledge Qiuli Bi for expert technical assistance during the course of these studies and Maiying Kong for expert consultation on statistical analysis.

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**Disclosures**

None.

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Intracoronary Delivery of Autologous Cardiac Stem Cells Improves Cardiac Function in a Porcine Model of Chronic Ischemic Cardiomyopathy

Roberto Bolli, Xian-Liang Tang, Santosh K. Sanganalmath, Ornella Rimoldi, Federico Mosna, Ahmed Abdel-Latif, Hani Jneid, Marcello Rota, Annarosa Leri and Jan Kajstura

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**SUPPLEMENTAL MATERIAL**

**METHODS**

**Induction of myocardial infarction and tissue harvest**

Male Yorkshire pigs (13.5 ± 0.8 kg, age 8–10 weeks) were anesthetized with an i.m. injection of ketamine (33 mg/kg) followed by an i.v. bolus of sodium pentobarbital (30 mg/kg). The animals were intubated and ventilated with 100% O$_2$; anesthesia was maintained with isoflurane (0.8-1.5%). Under sterile conditions, the heart was exposed by a median sternotomy and suspended in a pericardial cradle. The right atrial appendage was cross-clamped and the tip (1-2 g) resected for isolation of CSCs; the atrium was then sewed with a 5.0 prolene suture. The harvested atrial samples were rinsed in PBS, cut into small (1-2 mg) pieces, and snap frozen in a freezing medium composed of the growth culture medium pre-mixed with DMSO (9:1 vol/vol). The growth medium consisted of Ham’s F12 (BioWhittaker), 10% fetal bovine serum (Gibco) and penicillin/streptomycin (BioWhittaker).

A snare (3-0 silk suture) was placed around the left anterior descending (LAD) coronary artery, distal to the origin of the second diagonal branch. To produce MI, the snare was tightened for 90 min and then released; coronary reperfusion was visually confirmed by the reactive hyperemia. Pigs received lidocaine (2 mg/kg i.v. bolus followed by a 0.05 mg/kg/min infusion) and amiodarone (2 mg/kg i.v. bolus followed by a 0.04 mg/kg/min infusion) starting before coronary occlusion and ending 30 min after reperfusion. The chest was closed in layers. Animals received postoperative antibiotics (gentamicin 5 mg/kg i.m. and cefazolin 30 mg/kg i.m. daily for 3 d) and ketoprofen (2.5 mg/kg i.m. every 24 h for the first 48 h). A group of non-operated pigs was studied as normal controls. These animals did not undergo any surgical procedure and were
monitored for a period of time equivalent to the infarcted animals.

**Cardiac enzyme measurement**

Blood samples were obtained for serial measurement of cardiac markers before and immediately after catheterization and at 6, 12, 24 and 48 h thereafter. Cardiac markers, which included creatinine kinase (CK), creatinine kinase-MB fraction (CK-MB), troponin I (TnI), troponin T (TnT), myoglobin, and lactate dehydrogenase (LDH), were measured using standard human kits. As the cutoffs of normalcy for these proteins in pigs are unknown, relative changes in blood levels were utilized for intergroup comparisons (all of the aforementioned human assays were used after obtaining evidence of cross reactivity with porcine enzymes).

**Echocardiographic and hemodynamic studies**

Echocardiograms were obtained at baseline (before CSC delivery) and 31 d after CSC delivery (just before sacrifice) using an HDI 5000 ultrasound system (Philips Medical Systems) equipped with 4-2 MHz and 7-4 MHz phased array transducers. Before the echocardiographic study, pigs were anesthetized (isoflurane) and placed in the left lateral decubitus position. Temperature was monitored with a rectal temperature probe and kept between 37.0°C and 37.5°C with a heating pad. The parasternal long-axis, parasternal short-axis, and apical four-chamber views were used to obtain 2D, M-mode, and spectral Doppler images. Systolic and diastolic anatomic parameters were obtained from M-mode tracings at the mid-papillary level. Digital images were analyzed off-line by a single blinded observer using ProSolv (version 2.5) image analysis software (Problem Solving Concepts, Inc., Indianapolis, IN) according to the American Society of Echocardiography standards.
Two sets of hemodynamic measurements were performed under general anesthesia, before the start of the catheterization procedure and 31 d later (just before sacrifice). The left carotid artery was instrumented with a 6F sheath through which a 6F Millar micro-tip catheter pressure transducer (Millar Instruments Inc., Houston, TX) was placed and advanced into the LV cavity.

REFERENCES


## Supplemental table. Physiologic variables

<table>
<thead>
<tr>
<th></th>
<th>Vehicle-treated (n=10)</th>
<th>CSC-treated (n=11)</th>
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<tr>
<td><strong>Body weight (kg)</strong></td>
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<tr>
<td>At Surgery</td>
<td>13.1 ± 1.0</td>
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<td>At Catheterization</td>
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<tr>
<td>Week 1</td>
<td>46.0 ± 6.2</td>
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<td>Week 2</td>
<td>48.6 ± 6.2</td>
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<tr>
<td>Week 3</td>
<td>50.6 ± 6.6</td>
<td>49.1 ± 3.5</td>
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<tr>
<td>Week 4</td>
<td>52.6 ± 6.6</td>
<td>51.7 ± 3.4</td>
</tr>
<tr>
<td><strong>Heart rate (bpm) during surgery</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>During surgery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline (pre-thoracotomy)</td>
<td>116 ± 5</td>
<td>118 ± 12</td>
</tr>
<tr>
<td>Pre-occlusion</td>
<td>109 ± 5</td>
<td>106 ± 10</td>
</tr>
<tr>
<td>30 min occlusion</td>
<td>96 ± 6</td>
<td>91 ± 6</td>
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<tr>
<td>60 min occlusion</td>
<td>94 ± 4</td>
<td>87 ± 5</td>
</tr>
<tr>
<td>90 min occlusion</td>
<td>95 ± 7</td>
<td>85 ± 5</td>
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<tr>
<td>15 min reperfusion</td>
<td>92 ± 3</td>
<td>85 ± 6</td>
</tr>
<tr>
<td>30 min reperfusion</td>
<td>90 ± 5</td>
<td>84 ± 6</td>
</tr>
<tr>
<td>60 min reperfusion</td>
<td>81 ± 3</td>
<td>80 ± 5</td>
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<tr>
<td><strong>Mean arterial pressure (mmHg) during surgery</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>During surgery</td>
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<tr>
<td>Baseline (pre-thoracotomy)</td>
<td>67 ± 5</td>
<td>75 ± 7</td>
</tr>
<tr>
<td>Pre-occlusion</td>
<td>72 ± 4</td>
<td>70 ± 8</td>
</tr>
<tr>
<td>30 min occlusion</td>
<td>57 ± 4</td>
<td>65 ± 5</td>
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<tr>
<td>60 min occlusion</td>
<td>58 ± 3</td>
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<td>90 min occlusion</td>
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<tr>
<td>60 min reperfusion</td>
<td>56 ± 2</td>
<td>55 ± 3</td>
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<tr>
<td><strong>Electrolytes and hemoglobin before catheterization</strong></td>
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<tr>
<td>Hemoglobin</td>
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<tr>
<td>K⁺ (mmol/L)</td>
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<td>Na⁺ (mmol/L)</td>
<td>132.1 ± 3.6</td>
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<tr>
<td>HCT (%)</td>
<td>27.6 ± 0.7</td>
<td>27.4 ± 1.3</td>
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<tr>
<td><strong>Electrolytes and hemoglobin after catheterization</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hemoglobin</td>
<td>11.6 ± 0.7*</td>
<td>13.1 ± 1.2*</td>
</tr>
<tr>
<td>K⁺ (mmol/L)</td>
<td>4.6 ± 0.2</td>
<td>4.4 ± 0.2</td>
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<tr>
<td>Na⁺ (mmol/L)</td>
<td>129.0 ± 3.0</td>
<td>132.3 ± 3.6</td>
</tr>
<tr>
<td>HCT (%)</td>
<td>30.5 ± 3.0</td>
<td>25.4 ± 1.4</td>
</tr>
<tr>
<td><strong>Heart rate (bpm) during catheterization</strong></td>
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<tr>
<td>Pre inflation I</td>
<td>77 ± 2</td>
<td>89 ± 6</td>
</tr>
<tr>
<td>During inflation I</td>
<td>77 ± 2</td>
<td>84 ± 4</td>
</tr>
<tr>
<td>Pre-inflation II</td>
<td>77 ± 2</td>
<td>84 ± 4</td>
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<tr>
<td>During inflation II</td>
<td>76 ± 2</td>
<td>82 ± 4</td>
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<tr>
<td>Pre-inflation III</td>
<td>78 ± 2</td>
<td>88 ± 5</td>
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<td>During inflation III</td>
<td>76 ± 2</td>
<td>86 ± 4</td>
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<tr>
<td><strong>Mean arterial pressure (mmHg) during catheterization</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre inflation I</td>
<td>79 ± 5</td>
<td>68 ± 3</td>
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<tr>
<td>During inflation I</td>
<td>72 ± 8</td>
<td>62 ± 2</td>
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<td>Pre-inflation II</td>
<td>75 ± 6</td>
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<tr>
<td>During inflation II</td>
<td>72 ± 8</td>
<td>63 ± 2</td>
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<tr>
<td>Pre-inflation III</td>
<td>67 ± 7</td>
<td>65 ± 3</td>
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<tr>
<td>During inflation III</td>
<td>67 ± 7</td>
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* P<0.05 vs. value before catheterization.