Clinical Applications of Blood-Derived and Marrow-Derived Stem Cells for Nonmalignant Diseases

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STEM CELLS ARE UNDIFFERENTIATED cells that through replication have the capability of both self-renewal and differentiation into mature specialized cells. In broad terms, there are 2 types of stem cells, embryonic stem cells and adult stem cells. Human embryonic stem cells are isolated from a 50- to 150-cell, 4- to 5-day-old postfertilization blastocyst. Embryonic stem cells generate every specialized cell in the human body and, while capable of indefinite ex vivo proliferation, exist only transiently in vivo (during embryogenesis). Adult stem cells are located in tissues throughout the body and function as a reservoir to replace damaged or aging cells. Under physiologic conditions, adult stem cells are traditionally thought to be restricted in their differentiation to cell lineages of the organ system in which they are located.

Embryonic stem cells have great promise and versatility but, compared with adult stem cells, are currently difficult to control due to their tendency to form tumors containing all types of tissue, ie, teratomas. Embryonic stem cell biology has been associated with ethical controversy, and feeder cell-free and xenogeneic-free culture methods approved by the US Food and Drug Administration are still being per-
fected. In contrast, adult stem cells nor-
mally behave well without formation of
tumors and follow traditional lineage-
specific differentiation patterns, fulfill-
ing their physiologic homologous func-
tion of replacing normal turnover,
aging, or damaged tissues. For these rea-
sons, this review will be confined to
adult stem cells.

Due to the inability to efficiently and
safely harvest or expand stem cells from
most adult organs (eg, liver, gastroin-
testinal tract, heart, brain), the major-
ity of human stem cell trials have fo-
cused on clinical applications for
hematopoietic stem cells (HSCs), mes-
enchymal stem cells (MSCs), or both,
which can be easily obtained in clini-
cally sufficient numbers from periph-
eral blood, bone marrow, or umbilical
cord blood and placenta.

Bone marrow, peripheral blood stem
cells (PBSCs), and umbilical cord blood
are all sources of adult HSCs; however,
most of the cells in the collected prod-
uct are mature hematopoietic and im-
mune cells, rather than HSCs. To pu-
rify for HSCs, assays for their detection
needed to be developed. Hematopo-
etic stem cell assays may be divided into
surface antigen detection by flow cy-
tometry, clonogenic colony-forming as-
says, and in vivo transplant marrow re-
population assays. The gold standard for
HSCs is the ability to repopulate all he-
matopoietic lineages following marrow-
ablative total body irradiation. Serial
transplantation of stem cells from the
original transplant recipient into sec-
ondary and tertiary irradiated recipi-
ents reconstitutes hematopoiesis with re-
sultant normal life spans. Serial in vivo
transplantation demonstrates the 2 es-
sential functional criteria of HSCs: pro-
liferation to replenish the stem cell com-
partment (self-renewal) and lifelong
production of blood (terminal differen-
tiation).2,3

Human hematopoietic progenitor cells
are identified by glycoproteins CD34+, 
CD133+, or both. Most human marrow
or blood CD34+ or CD133+ cells are
committed progenitors, and only a minor-
ity are lifelong repopulating stem cells.
A CD34+ or CD133+-enriched HSC product
will reconstitute lifelong hematopoiesis
and may be easily purified from the mar-
ow or peripheral blood using commer-
cially available instruments.4,6

When cells from a bone marrow aspir-
ate are cultured in plastic flasks, he-
matopoietic cells and HSCs do not ad-
here to the plastic and are removed with
change of media. The remaining plastic-
adherent cells were originally termed
colony-forming unit fibroblasts be-
cause they formed fibroblast-like colo-
nies ex vivo.7 Subsequently, these ad-
herent cells have been termed MSCs, an
abbreviation for both mesenchymal stro-
mal cells and mesenchymal stem cells.

The former refers to the ability of MSCs
to contribute to the structural matrix of
designed to support hematopoiesis; the latter describes the ability of
MSCs to differentiate under various ex vivo culture conditions into different
mesenchymal-derived cells.

MSCs have no unique phenotypic
marker. The minimal criteria by the In-
ternational Society for Cellular Therapy
to define MSCs are (1) plastic-adherent
in culture; (2) expression of CD105,
CD73, and CD90; 3) lack of expression
of hematopoietic markers such as CD45,
CD34, CD14, CD11b, CD19, CD79a,
and HLA-DR; and 4) able to differenti-
ate into osteoblasts, adipocytes, and
chondrocytes. The ratio of MSCs to mar-
row mononuclear cells is estimated to be
only 10 MSCs per million marrow cells.9

Despite relatively low numbers, a 2-mL
aspirate of bone marrow can be ex-

duced 500-fold ex vivo to 12 billion to
35 billion MSCs within 3 weeks.9

EVIDENCE ACQUISITION

A search of multiple electronic data-
bases (MEDLINE, EMBASE, and Sci-
ence Citation Index), the Food and
Drug Administration Drug Site (http:
/www.fda.gov), and the National In-
istitutes of Health Web site (http://www
.clinicaltrials.gov) was conducted to
identify studies published from Janu-
ary 1997 to December 2007 on use of
hematopoietic, bone marrow, peripheral
blood, mesenchymal, or umbilical
cord blood stem cells in autoim-
mune, cardiac, or vascular disease. This
search was augmented by hand search-
ing of reference lists in clinical trials,
review articles, proceedings booklets,
Food and Drug Administration re-
ports, and contact with study authors
and device and pharmaceutical com-
panies. Author names that recurred re-
peatedly (≥6 times) within a given sub-
ject area were also searched for all
published reports.

The following data terms were in-
cluded in the search: stem cell transplan-
tation, bone marrow transplantation,
peripheral blood stem cell transplantation,
mesenchymal stem cell transplantation,
circulating progenitor cell, autoimmune
diseases, multiple sclerosis, systemic scler-
osis, systemic lupus erythematosus,
Crohn’s disease, rheumatoid arthritis, ju-
venile idiopathic arthritis, vasculitis, Weg-
ner’s, Sjögren’s, Behcet’s, celiac disease,
dermatomyositis, polymyositis, relaps-
ing polychondritis, chronic inflammatory
demyelinating polynuropathy, myasthe-
nia gravis, diabetes, coronary artery dis-
 ease, myocardial infarction, myocardial is-
chemia, coronary circulation, and
peripheral vascular disease. Animal data,
abstracts, and non–English-language
publications were excluded from the search.

EVIDENCE SYNTHESIS

Four reviewers (R.K.B., Y. W., Y.L., and
J.A.R.) judged eligibility of studies inde-
pendently and simultaneously. The ini-
tial search identified 926 articles (FIGURE).
Of these, 603 were excluded because they
were reviews, editorials, commentaries,
ethical discussions, or cancer-related. An-
other 323 were searched for toxicity and
feasibility. These included mechanistic,
stem cell collection, or toxicity reports,
treatment of relapse, multiple diseases
in a single report, interim or substudy
reports, and reports with a limited num-
ber of patients (≤3 patients with auto-
immune disorders, <10 with peripheral
vascular disease, <20 with chronic is-
chemic heart disease, or <30 with acute
ischemic heart disease).

Outcome was reviewed in 69 re-
ports (20 on acute ischemic heart dis-
ease that included ≥30 patients, 17 on
disease [≥20 patients], 6 on peripheral vascular disease [≥10 patients], and 26 on autoimmune disorders [≥4 patients] that reported on a single autoimmune disease and were not subsequently reported as part of a later study or analysis). These 69 reports included 854 patients with autoimmune diseases, 1002 patients with acute myocardial infarction, 493 patients with chronic myocardial ischemia, and 169 with peripheral vascular disease.

**Stem Cells for Autoimmune Diseases**

Hematopoietic stem cell transplantation (HSCT) for treatment of patients with severe autoimmune diseases began in the late 1990s. These clinical trials were based on extensive preclinical animal transplantation experiments. Some animal autoimmune diseases are environmentally induced by vaccination with self-peptides, adjuvant, or both and may be cured by a syngeneic or pseudoautologous (the animal equivalent of autologous) HSCT. The rationale of autologous HSCT for autoimmune diseases is to immune reset, ie, to generate new self-tolerant lymphocytes after chemotherapy-induced elimination of self- or auto-reactive lymphocytes (ie, lymphoablation). Other animal autoimmune disorders occur spontaneously without intentional or obvious environmental stimuli. These spontaneous-onset animal autoimmune diseases require allogeneic HSCT for cure. Allogeneic HSCT is based on the rationale of both immune reset (similar to autologous HSCT) and of correcting the genetic predisposition to disease by reinfusing non–disease-prone HSCs from a normal donor.

Treatment-related mortality for autologous HSCT of autoimmune diseases in the European Group for Blood and Marrow Transplantation registry is approximately 7%, and some trials have reported rates of up to 23%. Treatment-related mortality, although generally improving with greater experience and more careful patient selection, has justifiably dampened enthusiasm for the field. Autologous HSCT for autoimmune diseases may be performed with either myeloablative or nonmyeloablative regimens. Myeloablative regimens use cancer-specific treatments that destroy the entire marrow compartment, including marrow stem cells, resulting in irreversible and lethal marrow failure if HSCs are not reinfused. Nonmyeloablative regimens are designed specifically for autoimmune diseases, ie, for lymphoablation without irreversible destruction of marrow stem cells. Following a nonmyeloablative regimen, hematopoietic recovery will occur without infusion of HSCs; however, autologous HSCs provide support and shorten the duration of chemotherapy-induced marrow suppression.

The essential argument in favor of nonmyeloablative regimens is that treatment-related mortality needs to be very low for nonmalignant diseases, and nonmyeloablative regimens appear safer than myeloablative regimens (TABLE I). A percentage of patients may be cured by autologous HSCT, but—-independent of using a myeloablative or nonmyeloablative regimen—disease relapse may occur, and the incidence of serologic remissions and the correlation, if any, to duration of clinical remission has not been evaluated. Therefore, until and unless proven otherwise, autologous HSCT for autoimmune diseases should not be viewed as a cure but rather as changing the natural history of disease. This second point should be considered as the more realistic expectation in justifying mortality end points in favor of nonmyeloablative regimens.

A third point in favor of nonmyeloablative regimens is that immune-mediated diseases may, despite significant morbidity, remit or “burn out.” While probability of poor outcomes can be determined for a given population,
individual patients who may eventually remit or stabilize spontaneously cannot always be excluded a priori. It is debatable whether a subset of patients who may remit without HSCT should be exposed to myeloablative regimens, especially those including total body irradiation, which cause a relatively high incidence of a more lethal disease, ie, myelodysplastic syndrome (MDS)/leukemia. Treatment of systemic sclerosis and multiple sclerosis with myeloablative regimens including total body irradiation has already been reported to be complicated by

<p>| Table 1. Treatment-Related Mortality Following Autologous Hematopoietic Stem Cell Transplantation for Autoimmune Diseases^ |
|----------------------------------------|-----------------|-----------------|-----------------|------------------|</p>
<table>
<thead>
<tr>
<th>Source, Year</th>
<th>Disease</th>
<th>Multicenter</th>
<th>Treatment-Related</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burt et al, 2006</td>
<td>Relapsing-remitting MS</td>
<td>Single</td>
<td>0/21 (0)</td>
<td>0% progression at 2 y; 62% improved</td>
</tr>
<tr>
<td>Craig et al, 2007</td>
<td>Crohn disease</td>
<td>Single</td>
<td>0/21 (0)</td>
<td>100% remission; 33% relapse</td>
</tr>
<tr>
<td>Oyama et al, 2007</td>
<td>Systemic sclerosis</td>
<td>Single</td>
<td>0/10 (0)</td>
<td>70% progression-free survival at 2 y</td>
</tr>
<tr>
<td>Statkute et al, 2007</td>
<td>Vasculitis</td>
<td>Single</td>
<td>0/4 (0)</td>
<td>Complete remission (n = 3); partial response (n = 1)</td>
</tr>
<tr>
<td>Voltarelli et al, 2007</td>
<td>Type 1 diabetes mellitus</td>
<td>Single</td>
<td>0/15 (0)</td>
<td>13/15 patients remaining insulin-free</td>
</tr>
<tr>
<td>Vork et al, 2007</td>
<td>Systemic sclerosis</td>
<td>Multiple</td>
<td>1/26 (4)</td>
<td>64% event-free survival at 5 y^d</td>
</tr>
<tr>
<td>Burt et al, 2006</td>
<td>SLE</td>
<td>Single</td>
<td>1/50 (2)</td>
<td>50% disease-free survival at 5 y</td>
</tr>
<tr>
<td>Snowden et al, 2004</td>
<td>Rheumatoid arthritis</td>
<td>Multiple</td>
<td>0/73 (0)</td>
<td>50% ACR criteria 50 or greater response at 12 mo</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>2/220 (&lt;1)</td>
<td></td>
</tr>
<tr>
<td>Low-Intensity Myeloablative Regimen^</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al-toma et al, 2007</td>
<td>Celiac</td>
<td>Single</td>
<td>0/7 (0)</td>
<td>NA</td>
</tr>
<tr>
<td>Ni et al, 2006</td>
<td>Progressive MS^l</td>
<td>Single</td>
<td>2/21 (9.5)</td>
<td>42% progression-free survival at 42 mo</td>
</tr>
<tr>
<td>Xu et al, 2006</td>
<td>Secondary progressive MS</td>
<td>Single</td>
<td>0/22 (0)</td>
<td>77% progression-free survival</td>
</tr>
<tr>
<td>Capello et al, 2005</td>
<td>MS</td>
<td>Single</td>
<td>0/21 (0)</td>
<td>20 improved or stable</td>
</tr>
<tr>
<td>Carreras et al, 2003</td>
<td>MS</td>
<td>Single</td>
<td>0/14 (0)</td>
<td>3 improved</td>
</tr>
<tr>
<td>Fassas et al, 2002</td>
<td>Progressive MS^l</td>
<td>Single</td>
<td>1/24 (4)</td>
<td>78% improved or stabilized</td>
</tr>
<tr>
<td>Kozák et al, 2000</td>
<td>Secondary progressive MS</td>
<td>Single</td>
<td>0/8 (0)</td>
<td>3 improved</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>3/197 (&lt;2)</td>
<td></td>
</tr>
<tr>
<td>High-Intensity Myeloablative Regimen^</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nash et al, 2007</td>
<td>Systemic sclerosis</td>
<td>Multiple</td>
<td>8/34 (23)^j</td>
<td>64% progression-free survival at 5 y</td>
</tr>
<tr>
<td>Samijin et al, 2006</td>
<td>Secondary progressive MS</td>
<td>Single</td>
<td>1/14 (7)^j</td>
<td>64% 3-y disease progression</td>
</tr>
<tr>
<td>Burt et al, 2005</td>
<td>Secondary progressive MS</td>
<td>Single</td>
<td>1/21 (5)^j</td>
<td>38% progression in 2 y</td>
</tr>
<tr>
<td>Nash et al, 2003</td>
<td>Secondary progressive MS</td>
<td>Multiple</td>
<td>1/26 (4)</td>
<td>27% progression in 3 y</td>
</tr>
<tr>
<td>Openshaw et al, 2000</td>
<td>Secondary progressive MS</td>
<td>Single</td>
<td>2/5 (40)</td>
<td>NA</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>13/100 (13)</td>
<td></td>
</tr>
<tr>
<td>Mixed Myeloablative and Nonmyeloablative Regimens</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daiker et al, 2007</td>
<td>Vasculitis</td>
<td>Multiple</td>
<td>0/14 (0)</td>
<td>Complete remission (n = 6); partial response (n = 5)</td>
</tr>
<tr>
<td>Saccardi et al, 2006</td>
<td>MS^l</td>
<td>Multiple</td>
<td>10/178 (5.9)^m</td>
<td>63% improvement or stabilization</td>
</tr>
<tr>
<td>De Kleer et al, 2004</td>
<td>JIA</td>
<td>Multiple</td>
<td>3/34 (8)</td>
<td>53% complete remission</td>
</tr>
<tr>
<td>Farge et al, 2004</td>
<td>Systemic sclerosis</td>
<td>Multiple</td>
<td>5/57 (8.7)</td>
<td>Complete remission or partial response in 92%</td>
</tr>
<tr>
<td>Jayne et al, 2004</td>
<td>SLE</td>
<td>Multiple</td>
<td>7/53 (13)</td>
<td>55% disease-free survival at 5 y</td>
</tr>
<tr>
<td>Binks et al, 2001</td>
<td>Systemic sclerosis</td>
<td>Multiple</td>
<td>7/41 (17)</td>
<td>NA</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>32/337 (9.4)</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: ACR, American College of Rheumatology; CIDP, chronic inflammatory demyelinating polyneuropathy; JIA, juvenile idiopathic arthritis; MS, multiple sclerosis; NA, not available; SLE, systemic lupus erythematosus.

^Excludes reports having <4 patients, reports with multiple autoimmune diseases, and results included in interim or substudy analyses.

^Nonmyeloablative regimens include combinations of cyclophosphamide, fludarabine, or antilymphocyte antibodies.


^Progression-, relapse-, and mortality-free survival.

^Two patients received a myeloablative regimen.

^Low-intensity myeloablative regimens may include nonmyeloablative agents as well as either BEAM (carmustine, etoposide, cytarabine, melphalan) or melphalan (≤140 mg/m²).

^Not categorized as secondary or primary progressive.

^High-intensity myeloablative regimens may include nonmyeloablative agents as well as either total body irradiation (≥8 Gy) or full-dose busulfan.

^One case of late radiation-induced myelodysplastic syndrome/leukemia included in mortality.

^Includes primary and secondary progressive, relapsing progressive, and relapsing-remitting multiple sclerosis.

^Transplant-related mortality lower with less intense regimens.
MDS/leukemia,11,14 an occurrence consistent with the approximately 10% incidence of MDS after autologous HSCT using total body irradiation regimens in low-grade lymphomas.38,39

Independent of whether myeloablative or nonmyeloablative regimens are used, another complication, late secondary autoimmune disorders, may arise from some agents used in the conditioning regimen. The initial standard nonmyeloablative regimen of cyclophosphamide and rabbit antithymocyte globulin (rATG) was well tolerated. A second-generation nonmyeloablative regimen used cyclophosphamide and a broader- and longer-acting agent, alemtuzumab, instead of ATG. Potential life-threatening secondary autoimmune cytopenias, including idiopathic thrombocytopenic purpura, autoimmune neutropenia, and autoimmune hemolytic anemia, occurred late (2 to 18 months) after transplantation in patients receiving regimens containing alemtuzumab.50 A third-generation nonmyeloablative regimen, termed “rituximab sandwich,” entails 1 dose of rituximab given before and after cyclophosphamide and rATG. To date, this regimen has been well tolerated.

Both early and late toxicity are a consequence of the regimen used for transplantation and of the increase in transplant-related mortality that occurs with increased intensity of the transplant regimen. Treatment-related mortality is less than 1% for nonmyeloablative, less than 2% for low-intensity myeloablative, and 13% for high-intensity myeloablative regimens (Table 1). A number of reports combined data from patients treated with different conditioning regimens or from those with different diseases complicating interpretation, because toxicity is both regimen- and disease-specific (Table 1). Although transplant regimen intensity may correlate with remission duration it is unclear if, at some point in dose intensity, a response plateau occurs independent of any further increase in regimen intensity. It is also unclear if any regimen may be viewed as curative. However, myeloablative as well as nonmyeloablative regimens, regardless of intensity, when used during the inflammatory stage of disease, have demonstrated a potent disease-ameliorating and remission-inducing effect.

In a single experienced center, nonmyeloablative autologous HSCT for patients with systemic lupus erythematosus, when performed as salvage therapy for treatment-refractory disease, resulted in marked serologic, clinical, and organ improvement, with 2% (1/50) treatment-related mortality and 50% probability of maintaining remission for 5 years.20 In comparison, a multicenter analysis of HSCT for systemic lupus erythematosus that included both myeloablative and nonmyeloablative regimens from 23 different centers reported a similar 55% 5-year disease-free survival, but treatment-related mortality was 13% (7/53).56

In patients with systemic sclerosis, autologous HSCT resulted in remarkable reversal of skin tightness, improved joint flexibility and quality of life, and reversal of pulmonary alveolitis.15,18 Two studies of nonmyeloablative regimens demonstrated 0% (0/10) and 4% (1/26) rates of treatment-related mortality,17,18 respectively, while a study using a myeloablative approach including total body irradiation reported a rate of 23% (8/34).11 Both myeloablative11 and nonmyeloablative18 approaches reported identical 64% 5-year event-free survival.

For multiple sclerosis, original transplantation regimens were myeloablative and performed predominantly in patients with secondary progressive and, to a lesser extent, primary progressive disease. In this subset of patients, intense myeloablative regimens generally failed to improve neurologic disability or to convincingly halt or change the rate of progressive neurologic disability.27,29-31 High-intensity myeloablative regimens including total body irradiation or busulfan demonstrated high mortality (including MDS/leukemia),29-31 whereas BEAM (carmustine, etoposide, cytarabine, melphalan), a less intense myeloablative regimen and the most common regimen used in Europe for multiple sclerosis, was better tolerated with no deaths among the last 53 patients undergoing transplantation.31 Despite lack of clinical benefit in patients with progressive multiple sclerosis, magnetic resonance imaging evidence of inflammation was abrogated, while loss of brain volume continued for 2 years before subsiding.41

In retrospect, the predominant pathophysiology in primary and secondary progressive multiple sclerosis is axonal degeneration, which would not be expected to improve after autologous HSCT, a method that allows delivery of intense immune suppression. Learning from these studies, a trial of autologous HSCT for relapsing-remitting multiple sclerosis, which is an immune-mediated inflammatory disease, was performed with a safer nonmyeloablative regimen. There was no treatment-related mortality, no disease progression, and two-thirds of patients had significant improvement in neurologic function (R.K. Burt, Y. Loh, B. Cohen, et al; Autologous non-myeloablative hematopoietic stem cell transplantation for relapsing-remitting multiple sclerosis reverses neurologic disability; unpublished data, 2008).

The lessons learned from multiple sclerosis—ie, treat early while the disease is inflammatory and use nonmyeloablative regimens with low risk of treatment-related mortality—were applied to patients with type 1 diabetes by using a nonmyeloablative regimen and selecting patients within 6 weeks of diagnosis before complete loss of insulin-producing islet cells. Autologous nonmyeloablative HSCT resulted in insulin-free remission of type 1 diabetes in 13 of 19 patients, and some patients have maintained normal blood glucose levels (as determined by levels of glycated hemoglobin) despite no insulin or other therapy for more than 3 years at last follow-up.17

Both rheumatoid arthritis and Crohn disease have been treated almost exclusively with nonmyeloablative regimens (Table 1) (R.M. Craig, Y. Oyama, K. Quigley, et al; Autologous nonmyeloablative hematopoietic stem cell transplantation in patients with refractory Crohn disease; unpublished data, 2008).22,23 For rheumatoid arthritis, the majority achieved at least a 50% or greater response; demonstrated re-
newed responsiveness to traditional disease-modifying medications; had reduction in the rate of joint damage for at least 2 years after transplantation; and, when compared with baseline, had improvement on health status assessment questionnaires for at least 5 years. Crohn disease, an immune-mediated disorder that arises from dysregulated immune responses to intestinal pathogens rather than from autoantigens per se, also remitted following autologous nonmyeloablative HSCT (R.M. Craig, Y. Oyama, K. Quigley, et al; Autologous nonmyeloablative hematopoietic stem cell transplantation in patients with refractory Crohn disease; unpublished data, 2008). Other immune-mediated diseases that have been treated with encouraging initial results by autologous nonmyeloablative or low-intensity myeloablative regimens include chronic inflammatory demyelinating polyneuropathy, relapsing polychondritis, autoimmune-related retinitis and optic neuritis (Y. Oyama, R. K. Burt, C. Thirkell, E. Hanna, K. Merrill, J. Keltner; Autoimmune-related retinopathy and optic neuropathy [ARRON] syndrome treated by autologous nonmyeloablative hematopoietic stem cell transplantation; unpublished data, 2008), dermatomyositis/polymyositis, celiac disease, polyarteritis nodosa, neurovascular Behçet disease, neurovascular Sjögren syndrome, Takayasu arteritis, and Wegner granulomatosis. Although results are not yet reported, several randomized controlled trials of autologous HSCT for autoimmune diseases are ongoing, most of which use nonmyeloablative regimens (TABLE 2).

Recently, allogeneic HSCT using a sibling’s HSCs has also been reported for treatment of several autoimmune diseases. Because it changes genetic predisposition to disease, allogeneic HSCT is considered more likely to cure autoimmune diseases compared with autologous HSCT. Graft-vs-host disease (GVHD), an often more lethal immune-mediated disease, is not an acceptable risk following allogeneic HSCT for autoimmune disorders rather than for malignancies and should be minimized by depletion of lymphocytes from the donor graft. Although yet unproven, some animal and limited human data suggest that an allogeneic graft-vs-autoimmunity effect may occur without GVHD via use of a lymphocyte-depleted graft.

When administered intravenously without prior chemotherapy or radiotherapy, MSCs have an immune suppressive effect that can ameliorate animal autoimmune diseases, although the mechanisms remain poorly defined. Human trials of MSCs for numerous immune-mediated diseases are being discussed and have been initiated in patients with GVHD. Since MSCs can be easily obtained and culture-expanded, bone marrow– or adipose tissue–derived MSCs from third parties or from the original marrow donor have been infused to modulate refractory GVHD, with reports of beneficial effects in nonrandomized, noncontrolled trials. In nonrandomized trials, 94% of patients with acute GVHD responded to intravenous infusion of MSCs.

### Stem Cells for Vascular Disease

Numerous animal models of different disease states have reproducibly and repeatedly demonstrated improvement in nonhematopoietic organ function after injection of unmanipulated marrow, peripheral blood, or umbilical cord blood cells, or of enriched HSCs/MSCs. Possible mechanisms by which blood or marrow stem cells improve visceral organ function is cell fusion or transdifferentiation, ie, the phenomenon of in vivo transformation or epigenetic reprogramming of HSCs into somatic cells of nonmarrow, nonhematopoietic lineage such as cardiomyocytes or neurons. While cell fusion and transdifferentiation both may occur ex vivo, the preponderance of evidence suggests that in vivo these mechanisms are not clinically relevant.

The mechanism by which blood- and marrow-derived cells improve nonhematopoietic organ function may be attributable to vasculogenesis from endothelial progenitor cells contained within PBSCs or from bone marrow mononuclear cells (BMMCs) that undergo lineage-specific differentiation into new blood vessels; alternatively, a concept gaining broader acceptance is that numerous stem cells provide a local paracrine or cell-help-cell effect. This chaperone or paracrine effect is mediated through release of growth factors, antiapoptotic proteins, angiogenic proteins, or other trophic factors, immune-modulating factors, and improvement of function through physical remodeling of 3-dimensional architecture. While the exact mecha-

### Table 2. Ongoing Randomized Controlled Trials of Autologous Hematopoietic Stem Cell Transplantation for Autoimmune Diseases

<table>
<thead>
<tr>
<th>Trial</th>
<th>Disease</th>
<th>Country</th>
<th>URL (Trial Identifier)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASSIST</td>
<td>Systemic sclerosis</td>
<td>United States/Brazil</td>
<td><a href="http://www.clinicaltrials.gov">NCT00278525</a></td>
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<tr>
<td>ASTIL</td>
<td>Systemic lupus erythematosus</td>
<td>Europe</td>
<td>Pending</td>
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<tr>
<td>ASTIS</td>
<td>Systemic sclerosis</td>
<td>Europe</td>
<td><a href="http://www.astistrial.com">www.astistrial.com</a></td>
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<tr>
<td>KISS</td>
<td>Crohn disease</td>
<td>United States</td>
<td><a href="http://www.clinicaltrials.gov">NCT00271947</a></td>
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<tr>
<td>MIST</td>
<td>Multiple sclerosis</td>
<td>United States/Canada/Brazil</td>
<td><a href="http://www.clinicaltrials.gov">NCT00273364</a></td>
</tr>
</tbody>
</table>

**Nonmyeloablative Regimen**

**Myeloablative Regimen**

Abbreviations: ASSIST, American Scleroderma Stem Cell vs Immune Suppression Trial; ASTIL, Autologous Stem Cell Transplantation International Lupus; ASTIMS, Autologous Stem Cell Transplantation International Multiple Sclerosis; ASTIS, Autologous Stem Cell Transplantation International Scleroderma; KISS, Crohns Immune Suppression vs Stem Cells; MIST, Multiple Sclerosis International Stem Cell Transplant; SCOT, Scleroderma Cyclophosphamide Or Transplantation; URL, uniform resource locator.
nisms remain controversial, a substantial number of clinical trials have been initiated using BMBCs, PBSCs, purified HSCs, or cultured MSCs to treat vascular diseases.

**Acute Myocardial Infarction.** In patients with ST-segment elevation myocardial infarction, standard treatment, including percutaneous coronary intervention of the infarct-related artery with or without stent placement plus anticoagulation, has been followed several days to weeks later by repeat percutaneous coronary intervention and intracoronary infusion of stem cells.57-73 (Table 3). The infused stem cells have included autologous unmanipulated BMBCs, CD133- or CD34-purified HSCs, unselected PBSCs, MSCs, or circulating progenitor cells (CPCs), which are peripheral blood cells cultured ex vivo to express endothelial characteristics. This mixture of cells, whether unselected, enriched for a stem cell marker, or manipulated in culture and from diverse sources, can be used in intracoronary or intramyocardial transplantation without a clear distinction of superiority of one cellular source or type over another.

The TOPCARE-AMI (Transplantation of Progenitor Cells and Regeneration Enhancement in Acute Myocardial Infarction) study has published several reports comparing intracoronary transplantation of BMBCs with that of CPCs.57,74-77 BMBC- as well as CPC-treated patients had similar improvements in infarct size, left ventricular ejection fraction (LVEF), coronary blood flow, and perfusion. Benefit was maintained for at least 12 months.57

The REPAIR-AMI (Reinfusion of Enriched Progenitor Cells and Infarct Remodeling in Acute Myocardial Infarction) trial compared injection of intracoronary BMBCs with placebo 3 to 7 days after successful percutaneous coronary intervention and demonstrated improved recovery of left ventricular contractility in the cell treatment group.58 Benefit was also maintained for at least 12 months.99,100

The BOOST (Bone Marrow Transfer to Enhance ST-Elevation Infarct Regeneration) trial reported that BMBCs significantly improved LVEF 6 months after intracoronary transplantation.60 In contrast to the TOPCARE-AMI and REPAIR-AMI studies, the BOOST trial reported that the beneficial effect on LVEF was no longer significant after 12 months.61,62

### Table 3. Clinical Trials of Stem Cell Therapy for Acute Myocardial Infarction With ≥30 Patients

<table>
<thead>
<tr>
<th>Source</th>
<th>Trial</th>
<th>No. of Patients</th>
<th>Days After Acute MI</th>
<th>Follow-up, mo</th>
<th>Control/Infusion</th>
<th>Stem Cell Source</th>
<th>LVEF Outcome, Treatment/Control; Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choi et al,67 2007</td>
<td>Unblinded</td>
<td>73</td>
<td>5-19</td>
<td>24</td>
<td>None</td>
<td>Peripheral blood</td>
<td>NS</td>
</tr>
<tr>
<td>Kang et al,65 2006</td>
<td>MAGIC Cell 1</td>
<td>30</td>
<td>NAa</td>
<td>24</td>
<td>G-CSF</td>
<td>Peripheral blood</td>
<td>Improved in infusion group compared to G-CSF</td>
</tr>
<tr>
<td>Li et al,70 2007</td>
<td>Unblinded</td>
<td>70</td>
<td>6</td>
<td>6</td>
<td>Untreated</td>
<td>Peripheral blood</td>
<td>Improved 7.1%/1.6%</td>
</tr>
<tr>
<td>Tatsurumi et al,71 2007</td>
<td>Unblinded</td>
<td>54</td>
<td>&lt;5</td>
<td>6</td>
<td>None</td>
<td>Peripheral blood</td>
<td>Improved 13.4%/7.4%</td>
</tr>
<tr>
<td>Janssens et al,72 2006</td>
<td>Randomized</td>
<td>67</td>
<td>1-2</td>
<td>4</td>
<td>Placebo</td>
<td>Bone marrow</td>
<td>3.3%/2.2% reduced infarct size (NS)</td>
</tr>
<tr>
<td>Kang et al,66 2006</td>
<td>MAGIC Cell-3-DES</td>
<td>82</td>
<td>NA</td>
<td>6</td>
<td>Acute MI/old MI/un-treated</td>
<td>Peripheral blood</td>
<td>Improved 5.1%--/−0.2%</td>
</tr>
<tr>
<td>Lunde et al,68 2006</td>
<td>ASTAMI</td>
<td>100</td>
<td>4-8</td>
<td>6</td>
<td>None</td>
<td>Bone marrow</td>
<td>Improved 3.1%/2.1% (NS)</td>
</tr>
<tr>
<td>Meyer et al,69 2006</td>
<td>BOOST</td>
<td>60</td>
<td>4.5b</td>
<td>18</td>
<td>None</td>
<td>Bone marrow</td>
<td>Improved 5.9%/3.1% (NS)</td>
</tr>
<tr>
<td>Mansour et al,70 2006</td>
<td>Nonrandomized</td>
<td>38</td>
<td>NA</td>
<td>4-8</td>
<td>None</td>
<td>CD133</td>
<td>LVEF not examined; increased infarct-related artery restenosis</td>
</tr>
<tr>
<td>Meluzín et al,71 2006</td>
<td>Randomizedc</td>
<td>66</td>
<td>5-9</td>
<td>3</td>
<td>None</td>
<td>Bone marrow</td>
<td>Improved 5%/2% in high dose</td>
</tr>
<tr>
<td>Schächinger et al,72 2006</td>
<td>REPAIR-AMI</td>
<td>204</td>
<td>3-7</td>
<td>4</td>
<td>Placebo</td>
<td>Bone marrow</td>
<td>Improved 5.5%/3.0%</td>
</tr>
<tr>
<td>Schächinger et al,73 2006</td>
<td>REPAIR-AMI</td>
<td>204</td>
<td>3-7</td>
<td>12</td>
<td>Placebo</td>
<td>Bone marrow</td>
<td>Improved outcome of death, reinfarction, revascularization</td>
</tr>
<tr>
<td>Schaefer et al,74 2006</td>
<td>BOOST</td>
<td>59</td>
<td>4.5c</td>
<td>18</td>
<td>None</td>
<td>Bone marrow</td>
<td>Improved diastolic function (NS)</td>
</tr>
<tr>
<td>Bartunek et al,75 2005</td>
<td>Unblinded</td>
<td>35</td>
<td>11.6c</td>
<td>4</td>
<td>None</td>
<td>CD133</td>
<td>Improved/Increased infarct-related artery restenosis</td>
</tr>
<tr>
<td>Chen et al,76 2004</td>
<td>Randomized</td>
<td>69</td>
<td>&gt;18</td>
<td>6</td>
<td>Placebo</td>
<td>Mesenchymal</td>
<td>Improved 18%/6%</td>
</tr>
<tr>
<td>Schächinger et al,77 2004</td>
<td>TOPCARE-AMI</td>
<td>54</td>
<td>3-7</td>
<td>12</td>
<td>None</td>
<td>Bone marrow or CPCs</td>
<td>Improved 8% for both bone marrow and CPCs at 4 mo</td>
</tr>
<tr>
<td>Wollert et al,78 2004</td>
<td>BOOST</td>
<td>60</td>
<td>4.8d</td>
<td>6</td>
<td>None</td>
<td>Bone marrow</td>
<td>Improved 6.7%/0.7%</td>
</tr>
</tbody>
</table>

**Abbreviations:** ASTAMI, Autologous Stem Cell Transplantation in Acute Myocardial Infarction; BOOST, Bone Marrow Transfer to Enhance ST Elevation Infarct Regeneration Trial; CPC, circulating progenitor cell; G-CSF, granulocyte colony-stimulating factor; LVEF, left ventricular ejection fraction; MAGIC, Myocardial Regeneration and Angiogenesis in Myocardial Infarction With G-CSF and Intracoronary Stem Cell Infusion; MAGIC Cell-3-DES, MAGIC-3-Drug Eluting Stents; MI, myocardial infarction; NA, not available; NS, not significant; REPAIR-AMI, Reinfusion of Enriched Progenitor Cells and Infarct Remodeling in Acute Myocardial Infarction; TOPCARE-AMI, Transplantation of Progenitor Cells and Regeneration Enhancement in Acute Myocardial Infarction.

*aStudy assessed both acute and old MI.

*bMean value.

cRandomized to high-dose, low-dose, or no cells.

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The ASTAMI (Autologous Stem Cell Transplantation in Acute Myocardial Infarction) trial found no significant beneficial effects from intracoronary transplantation of BMMCs on LVEF. Compared with controls, BMMCs tended to improve LVEF as demonstrated by echocardiography (3.1%-2.1%) and single photon emission computed tomography (8.1%-7.0%) and tended to diminish infarct size (~11% to ~7.8%). These changes were not significantly different.

The MAGIC (Myocardial Regeneration and Angiogenesis in Myocardial Infarction With G-CSF and Intracoronary Stem Cell Infusion) Cell 1 study compared intracoronary transplantation of granulocyte colony–stimulating factor (G-CSF)–mobilized PBSCs vs treatment with G-CSF alone vs an untreated control group. Left ventricular ejection fraction improved in the PBSC group compared with the G-CSF-alone group, and there was an increase in restenosis in patients receiving G-CSF. The subsequent MAGIC Cell-3-DES (Myocardial Regeneration and Angiogenesis in Myocardial Infarction With G-CSF and Intracoronary Stem Cell Infusion-3-Drug Eluting Stents) study compared intracoronary transplantation of G-CSF–mobilized PBSCs vs an untreated control group. Left ventricular ejection fraction and remodeling improved compared with controls in the cell-treated group with acute myocardial infarction. Significant improvement in LVEF has been reported following injection of MSCs as well as of BMMCs, CPCs, and PBSCs.

Taken as a whole, the results of intracoronary transplantation of progenitor cells following ST-segment elevation acute myocardial infarction are generally viewed as conveying a modest benefit. Single-group studies must be tempered by the realization that LVEF normally improves a few months after acute myocardial infarction, even without stem cell transplantation. Interstudy and intrastudy reproducibility of LVEF demonstrated by echocardiography and cardiovascular magnetic resonance imaging varies significantly, with conservative estimates of 8.6% and 2.4%, respectively. Reproducibility of LVEF measurement, therefore, overlaps with anticipated improvement (2%-5%) from stem cell transplantation. Nevertheless, 3 separate meta-analyses of controlled clinical trials of stem cell therapy in acute myocardial infarction have indicated modest benefit.

**Chronic Coronary Artery Disease.** In chronic ischemic cardiac disease or old myocardial infarction, noncontracting but viable myocardium, termed hibernating myocardium, is a physiologic response to hypoxic stress that halts the energy demands of contraction to prevent cardiomyocyte death. In the laboratory, hibernating myocardium is identified by areas of electromechanical dissociation, ie, myocardium that conducts electricity but does not contract.

Initial trials using stem cells in old myocardial infarction or chronic ischemia involved thoracotomy and coronary artery bypass graft surgery with simultaneous epicardial-directed intramyocardial injection of BMMCs or PBSCs while the heart was still arrested during cardiopulmonary bypass. Subsequently, most patients with chronic ischemic heart disease received stem cells by either percutaneous intracoronary or endomyocardial delivery without undergoing simultaneous coronary artery bypass graft surgery. Erbs et al treated chronic (>30-day) total coronary occlusion with recanalization, followed 10 days later by randomization to intracoronary CPC infusion or no cells. Patients receiving CPCs had significant improvement in LVEF. In the IACT (Intracoronary Autologous Bone Marrow Cell Transplantation in Chronic Coronary Artery Disease) trial, Strauer et al treated old myocardial infarction (5 months to 8.5 years prior) with intracoronary BMMCs, with significant improvement in LVEF. Assmus et al randomized 75 patients in the TOPCARE-CHD (Transplantation of Progenitor Cells and Recovery of Left Ventricular Function in Patients With Chronic Ischemic Heart Disease) trial to intracoronary infusion of BMMCs, CPCs, or no cells. Bone marrow mononuclear cells, but not CPCs, improved LVEF compared with controls; if heart failure was present, injection of BMMCs resulted in significant reduction of brain natriuretic peptide, a serum marker for heart failure.

In summary, pump failure has been a historically vexing problem and, despite maximizing medical therapy, often progressive and irreversible. Symptomatic relief of pain may be a placebo effect. Nevertheless, stem cell treatment of chronic myocardial ischemia has generally been reported to increase regional perfusion, wall motion, and global LVEF; and to relieve angina pectoris. A recent meta-analysis reported a modest association between blood- or marrow-derived stem cell injection and improvement in chronic ischemic heart disease.

**Peripheral Vascular Disease.** Tissue limb ischemia from peripheral vascular disease usually manifests in the lower extremities and may be due to thromboangiitis obliterans (Buerger disease) or atherosclerosis obliterans. The mainstay of treatment for peripheral vascular disease has been surgical revascularization. Patients with critical limb ischemia that have exhausted operative revascularization procedures are traditionally treated by limb amputation. Several reports have suggested that injection of blood- or bone marrow–derived stem cells into the affected limb may have some benefit. As in cardiac disease, a variety of stem cell sources have been used, including unselected bone marrow, G-CSF–mobilized PBSCs, MSCs, CPCs, and purified CD34 or CD133 stem cells obtained from marrow or peripheral blood.

Progenitor cells are injected directly via a syringe through a 22- to 26-gauge needle into multiple sites 1 to 3 cm apart into the gastrocnemius/soleus muscle or into the foot or quadriceps muscle, or both, of the involved leg. The procedure has generally been performed safely, although 1 case of an arteriovenous fistula at the injection site has been reported. While most investigators prefer percutaneous injection into the
muscle, equally encouraging results are obtained by intra-arterial injection of cells into the involved extremity or by fenestration (ie, puncturing the tibia) to allow bone marrow cells to leak into adjacent muscle.101-103

Most patients experience relief of symptomatic pain, limb salvage, and functional improvement. In some cases, ischemic ulcer healing and the ankle-brachial index (a measure of ankle blood flow) improves. In 2 studies, all patients with thromboangiitis obliterans responded to therapy.103,104 In contrast, depending on the report, approximately two-thirds (70%) of patients with atherosclerosis obliterans responded.105

The TACT (Therapeutic Angiogenesis by Cell Transplantation) trial enrolled patients with bilateral (n = 22) or unilateral (n = 25) peripheral vascular disease.106 Investigators injected one leg with BMMCs and the other with blood. The pain-free walking time, ankle-brachial index, and capillary venous oxygen saturation significantly improved in the BMMC-injected legs compared with those injected with blood. A second randomized trial, TAM-PAD (Transplant of Autologous Mononuclear Bone Marrow Cells in Peripheral Arterial Disease), combined intra-arterial and intramuscular injection of BMMCs.102 The group receiving BMMCs (n = 13) had significantly improved pain-free walking time, ankle-brachial index, and capillary venous oxygen saturation.102

Duration of improvement following injection of progenitor cells remains unclear but may persist beyond 1 year. The dose of injected CD34+ cells may affect efficacy.107 Injected BMMCs are thought to secrete numerous cytokines, such as vascular endothelial growth factor, that may induce local angiogenesis, recruit circulating CD34+ cells for vasculogenesis, or release factors such as nitric oxide that augment local endothelial cell attempts at vasodilation.108

**COMMENT**

The use of adult HSCs is rapidly expanding beyond the traditional applications for malignancy. In autoimmune diseases, chemotherapy to ablate the disease-causing immune system is followed by infusion of unmanipulated autologous bone marrow, PBSCs, or purified CD34+ HSCs to reconstitute immunopoiesis or hematopoiesis. Autologous HSCT, while probably not a “cure,” appears to be a potentially useful clinical approach available to ameliorate autoimmune disease activity. However, HSCT has been complicated by significant treatment-related mortality and late MDS/leukemia when intense myeloablative regimens are used, indicating the need for development of safer nonmyeloablative regimens and restriction of this technique to experienced centers. Allogeneic (sibling or umbilical cord blood) transplantation of HSCs ultimately may prove to be the elusive “cure” for some autoimmune disorders, but allogeneic HSCT must be performed without risk of GVHD by lymphocyte depletion of the donor graft, and whether an allogeneic graft-vs-autoimmunity effect can occur without GVHD remains unproven.

Unmanipulated bone marrow, peripheral blood stem cells, and purified HSCs and MSCs infused without prior chemotherapy have been used to facilitate tissue repair following ischemic injury. Randomized trials have suggested modest benefit with little toxicity from stem

**Table 4. Clinical Trials of Stem Cell Therapy for Chronic Myocardial Ischemia and/or Heart Failure With ≥20 Patients**

<table>
<thead>
<tr>
<th>Source</th>
<th>Trial Type/Name</th>
<th>No. of Patients Follow-up, mo</th>
<th>Stem Cell Route</th>
<th>Stem Cell Source</th>
<th>LVEF Outcome; Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assmus et al.106 2007</td>
<td>TOPCARE-CHD</td>
<td>121</td>
<td>Intra coronary</td>
<td>Bone marrow</td>
<td>Improved mortality in high-order CFUs injected</td>
</tr>
<tr>
<td>Losordo et al.107 2007</td>
<td>Randomized</td>
<td>21</td>
<td>Intramyocardial</td>
<td>CD34</td>
<td>Not examined</td>
</tr>
<tr>
<td>Manginas et al.108 2007</td>
<td>Unblinded</td>
<td>24</td>
<td>Intra coronary</td>
<td>CD133, CD34</td>
<td>Improved LVEF and left ventricular volumes</td>
</tr>
<tr>
<td>Stamm et al.109 2007</td>
<td>Unblinded</td>
<td>40</td>
<td>Intramyocardial</td>
<td>CD133</td>
<td>Improved LVEF</td>
</tr>
<tr>
<td>Assmus et al.110 2006</td>
<td>TOPCARE-CHD</td>
<td>75</td>
<td>Intra coronary</td>
<td>Bone marrow/CPCs</td>
<td>Improved with bone marrow</td>
</tr>
<tr>
<td>Beeres et al.111 2006</td>
<td>Single group</td>
<td>25</td>
<td>Intramyocardial</td>
<td>Bone marrow</td>
<td>Improved LVEF, CCS angina score, perfusion</td>
</tr>
<tr>
<td>Chen et al.112 2006</td>
<td>Unblinded</td>
<td>45</td>
<td>Intra coronary</td>
<td>Mesenchymal</td>
<td>Improved ischemia, NYHA class, and LVEF</td>
</tr>
<tr>
<td>Fuchs et al.113 2006</td>
<td>Single group</td>
<td>27</td>
<td>Intramyocardial</td>
<td>CD34</td>
<td>Improved CCS angina score</td>
</tr>
<tr>
<td>Gao et al.114 2006</td>
<td>Unblinded</td>
<td>28</td>
<td>Intra coronary</td>
<td>Bone marrow</td>
<td>Improved LVEF, improvement in CHF</td>
</tr>
<tr>
<td>Hendrix et al.115 2006</td>
<td>Randomized</td>
<td>20</td>
<td>Intramyocardial</td>
<td>Bone marrow</td>
<td>NS</td>
</tr>
<tr>
<td>Mocini et al.116 2006</td>
<td>CABG + cells or CABG alone</td>
<td>36</td>
<td>Intramyocardial</td>
<td>Bone marrow</td>
<td>Improved LVEF and wall motion</td>
</tr>
<tr>
<td>Erbs et al.117 2005</td>
<td>Randomized</td>
<td>26</td>
<td>Intra coronary</td>
<td>CPCs</td>
<td>Improved</td>
</tr>
<tr>
<td>Patel et al.118 2006</td>
<td>Randomized</td>
<td>26</td>
<td>Intramyocardial</td>
<td>CD34</td>
<td>Improved</td>
</tr>
<tr>
<td>Strauer et al.119 2005</td>
<td>IACTa</td>
<td>36</td>
<td>Intra coronary</td>
<td>Bone marrow</td>
<td>Improved</td>
</tr>
<tr>
<td>Perin et al.120 2004</td>
<td>Sequential enrollment; treatment or control</td>
<td>20</td>
<td>Intramyocardial</td>
<td>Bone marrow</td>
<td>NS</td>
</tr>
<tr>
<td>Perin et al.121 2003</td>
<td>Single group</td>
<td>21</td>
<td>Intramyocardial</td>
<td>Bone marrow</td>
<td>Improved</td>
</tr>
</tbody>
</table>

**Abbreviations:** CABG, coronary artery bypass graft; CCS, Canadian Cardiovascular Society; CFU, colony-forming unit; CHF, congestive heart failure; CPC, circulating progenitor cell; IACT, Intracoronary Autologous Bone Marrow Cell Transplantation in Chronic Coronary Artery Disease; LVEF, left ventricular ejection fraction; NS, not significant; NT-proBNP, N-terminal pro-brain natriuretic peptide; NYHA, New York Heart Association; TOPCARE-CHD, Transplantation of Progenitor Cells and Recovery of Left Ventricular Function in Patients With Chronic Ischemic Heart Disease.

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BLOOD- AND MARROW-DERIVED STEM CELLS FOR NONMALIGNANT DISEASES

Cell therapy in cardiac disease and peripheral vascular disease. The mechanisms of this effect remain undefined and have evolved from cell fusion and transdifferentiation to endothelial progenitor cell–derived vasculogenesis and local paracrine effects. Clinical trials are needed to determine the most appropriate cell type, dose, method, and timing of delivery for use of HSCs in cardiovascular disease. Similar trials are also being considered or have recently been initiated in liver disease.109-111 cerebrovascular disease, and spinal cord injury.

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Author Contributions: Dr Burt had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

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Analysis and interpretation of data: Burt, Pearce, Beohar, Craig, Rapp, Kessler.

Drafting of the manuscript: Burt, Beohar.

Critical revision of the manuscript for important intellectual content: Burt, Loh, Pearce, Beohar, Barr, Craig, Wenn, Rapp, Kessler.

Administrative, technical, or material support: Burt, Loh, Beohar, Barr, Wenn.

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tients with refractory chronic heart failure secondary
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lot study to evaluate the safety and feasibility of in-
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peripheral arterial occlusive disease and critical limb
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