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

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Context  Stem cell therapy is rapidly developing and has generated excitement and promise as well as confusion and at times contradictory results in the lay and scientific literature. Many types of stem cells show great promise, but clinical application has lagged due to ethical concerns or difficulties in harvesting or safely and efficiently expanding sufficient quantities. In contrast, clinical indications for blood-derived (from peripheral or umbilical cord blood) and bone marrow-derived stem cells, which can be easily and safely harvested, are rapidly increasing.

Objective  To summarize new, nonmalignant, nonhematologic clinical indications for use of blood- and bone marrow-derived stem cells.

Evidence Acquisition  Search of multiple electronic databases (MEDLINE, EMBASE, Science Citation Index), US Food and Drug Administration [FDA] Drug Site, and National Institutes of Health Web site to identify studies published from January 1997 to December 2007 on use of hematopoietic stem cells (HSCs) in autoimmune, cardiac, or vascular diseases. The search was augmented by hand searching of reference lists in clinical trials, review articles, proceedings booklets, FDA reports, and contact with study authors and device and pharmaceutical companies.

Evidence Synthesis  Of 926 reports identified, 323 were examined for feasibility and toxicity, including those with small numbers of patients, interim or substudy reports, and reports on multiple diseases, treatment of relapse, toxicity, mechanism of action, or stem cell mobilization. Another 69 were evaluated for outcomes. For autoimmune diseases, 26 reports representing 854 patients reported treatment-related mortality of less than 1% (2/220 patients) for nonmyeloablative, less than 2% (3/197) for dose-reduced myeloablative, and 13% (13/100) for intense myeloablative regimens, ie, those including total body irradiation or high-dose busulfan. While all trials performed during the inflammatory stage of autoimmune disease suggested that transplantation of HSCs may have a potent disease-remitting effect, remission duration remains unclear, and no randomized trials have been published. For reports involving cardiovascular diseases, including 17 reports involving 1002 patients with acute myocardial infarction, 16 involving 493 patients with chronic coronary artery disease, and 3 meta-analyses, the evidence suggests that stem cell transplantation performed in patients with coronary artery disease may contribute to modest improvement in cardiac function.

Conclusions  Stem cells harvested from blood or marrow, whether administered as purified HSCs or mesenchymal stem cells or as an unmanipulated or unpurified product can, under appropriate conditions in select patients, provide disease-ameliorating effects in some autoimmune diseases and cardiovascular disorders. Clinical trials are needed to determine the most appropriate cell type, dose, method, timing of delivery, and adverse effects of adult HSCs for these and other nonmalignant disorders.

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fected. In contrast, adult stem cells normally behave well without formation of tumors and follow traditional lineage-specific differentiation patterns, fulfilling their physiologic homologous function of replacing normal turnover, aging, or damaged tissues. For these reasons, 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, gastrointestinal tract, heart, brain), the majority of human stem cell trials have focused on clinical applications for hematopoietic stem cells (HSCs), mesenchymal stem cells (MSCs), or both, which can be easily obtained in clinically sufficient numbers from peripheral 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 product are mature hematopoietic and immune cells, rather than HSCs. To purify for HSCs, assays for their detection needed to be developed. Hematopoietic stem cell assays may be divided into surface antigen detection by flow cytometry, clonogenic colony-forming assays, and in vivo transplant marrow re-population assays.1 The gold standard for HSCs is the ability to repopulate all hematopoietic lineages following marrow-ablative total body irradiation. Serial transplantation of stem cells from the original transplant recipient into secondary and tertiary irradiated recipients reconstitutes hematopoiesis with resultant normal life spans. Serial in vivo transplantation demonstrates the 2 essential functional criteria of HSCs: proliferation to replenish the stem cell compartment (self-renewal) and lifelong production of blood (terminal differentiation).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 minority are lifelong repopulating stem cells. A CD34+ or CD133-enriched HSC product will reconstitute lifelong hematopoiesis and may be easily purified from the marrow or peripheral blood using commercially available instruments.4,5

When cells from a bone marrow aspirate are cultured in plastic flasks, hematopoietic cells and HSCs do not adhere to the plastic and are removed with change of media. The remaining plastic-adherent cells were originally termed colony-forming unit fibroblasts because they formed fibroblast-like colonies ex vivo.6 Subsequently, these adherent cells have been termed MSCs, an abbreviation for both mesenchymal stromal cells and mesenchymal stem cells. The former refers to the ability of MSCs to contribute to the structural matrix of bone marrow and 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 International Society of 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 differentiate into osteoblasts, adipocytes, and chondrocytes.8 The ratio of MSCs to marrow 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 expanded 500-fold ex vivo to 12 billion to 35 billion MSCs within 3 weeks.9

**EVIDENCE ACQUISITION**

A search of multiple electronic databases (MEDLINE, EMBASE, and Science Citation Index), the Food and Drug Administration Drug Site (http://www.fda.gov), and the National Institutes of Health Web site (http://www.clinicaltrials.gov) was conducted to identify studies published from January 1997 to December 2007 on use of hematopoietic, bone marrow, peripheral blood, mesenchymal, or umbilical cord blood stem cells in autoimmune, cardiac, or vascular disease. This search was augmented by hand searching of reference lists in clinical trials, review articles, proceedings booklets, Food and Drug Administration reports, and contact with study authors and device and pharmaceutical companies. Author names that recurs repeatedly (≥6 times) within a given subject area were also searched for all published reports.

The following data terms were included in the search: stem cell transplantation, bone marrow transplantation, peripheral blood stem cell transplantation, hematopoietic stem cell transplantation, mesenchymal stem cell transplantation, circulating progenitor cell, autoimmune diseases, multiple sclerosis, systemic sclerosis, systemic lupus erythematosus, Crohn’s disease, rheumatoid arthritis, juvenile idiopathic arthritis, vasculitis, Wegner’s, Sjögren’s, Behcet’s, celiac disease, dermatomyositis, polymyositis, relapsing polychondritis, chronic inflammatory demyelinating polyneuropathy, myasthenia gravis, diabetes, coronary artery disease, myocardial infarction, myocardial ischemia, 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 independently and simultaneously. The initial search identified 926 articles (Figure). Of these, 603 were excluded because they were reviews, editorials, commentaries, ethical discussions, or cancer-related. Another 323 were examined 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 number of patients (≤3 patients with autoimmune disorders, <10 with peripheral vascular disease, <20 with chronic ischemic heart disease, or <30 with acute ischemic heart disease).

Outcome was reviewed in 69 reports (20 on acute ischemic heart disease that included ≥30 patients, 17 on...
disease \([\geq 20\text{ patients}]\), 6 on peripheral vascular disease \([\geq 10\text{ patients}]\), and 26 on autoimmune disorders \([\geq 4\text{ patients}]\) 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%,\(^6\) and some trials have reported rates of up to 23%.\(^1\) 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.\(^2\) 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.\(^3\)

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\(^1\)^{1,14,37} (TABLE I).

Figure. Flow of Eligible Studies of Stem Cell Transplantation for Nonmalignant Nonhematologic Diseases

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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.\(^\text{12}\) Treatment of systemic sclerosis and multiple sclerosis with myeloablative regimens including total body irradiation has already been reported to be complicated by

<table>
<thead>
<tr>
<th>Source</th>
<th>Disease</th>
<th>Multicenter or Single Center</th>
<th>Treatment-Related Deaths/Patients, No. (%)</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burt et al(^\text{2})</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(^\text{d})</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,(^\text{15}) 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,(^\text{16}) 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,(^\text{17}) 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,(^\text{18}) 2007</td>
<td>Systemic sclerosis</td>
<td>Multiple</td>
<td>1/26 (4)</td>
<td>64% event-free survival at 5 y(^\text{a})</td>
</tr>
<tr>
<td>Burt et al,(^\text{19}) 2006</td>
<td>SLE</td>
<td>Single</td>
<td>1/50 (2)</td>
<td>50% disease-free survival at 5 y</td>
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<tr>
<td>Snowden et al,(^\text{21}) 2004</td>
<td>Rheumatoid arthritis</td>
<td>Multiple</td>
<td>0/73 (0)(^\text{f})</td>
<td>50% ACR criteria 50 or greater response at 12 mo</td>
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<tr>
<td>Total</td>
<td></td>
<td></td>
<td>2/220 (&lt;1)</td>
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### Low-Intensity Myeloablative Regimen\(^\text{b}\)

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<th>Response</th>
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<tr>
<td>Ni et al,(^\text{22}) 2006</td>
<td>Progressive MS(^\text{11})</td>
<td>Single</td>
<td>2/21 (9.5)</td>
<td>42% progression-free survival at 42 mo</td>
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<tr>
<td>Xu et al,(^\text{23}) 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,(^\text{24}) 2006</td>
<td>MS</td>
<td>Single</td>
<td>0/21 (0)</td>
<td>20 improved or stable</td>
</tr>
<tr>
<td>Carreras et al,(^\text{25}) 2006</td>
<td>MS</td>
<td>Single</td>
<td>0/14 (0)</td>
<td>3 improved</td>
</tr>
<tr>
<td>Fassas et al,(^\text{26}) 2007</td>
<td>Progressive MS(^\text{11})</td>
<td>Single</td>
<td>1/24 (4)</td>
<td>78% improved or stabilized</td>
</tr>
<tr>
<td>Kozák et al,(^\text{27}) 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>
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### High-Intensity Myeloablative Regimen\(^\text{i}\)

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<tr>
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<th>Treatment-Related Deaths/Patients, No. (%)</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nash et al,(^\text{11}) 2007</td>
<td>Systemic sclerosis</td>
<td>Multiple</td>
<td>8/34 (23)(^\text{f})</td>
<td>64% progression-free survival at 5 y</td>
</tr>
<tr>
<td>Samijin et al,(^\text{14}) 2006</td>
<td>Secondary progressive MS</td>
<td>Single</td>
<td>1/14 (7)(^\text{f})</td>
<td>64% 3-y disease progression</td>
</tr>
<tr>
<td>Burt et al,(^\text{29}) 2003</td>
<td>Secondary progressive MS</td>
<td>Single</td>
<td>1/21 (5)(^\text{f})</td>
<td>38% progression in 2 y</td>
</tr>
<tr>
<td>Nash et al,(^\text{28}) 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,(^\text{29}) 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>13/100 (13)</td>
<td></td>
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</table>

### Mixed Myeloablative and Nonmyeloablative Regimens

<table>
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<th>Source</th>
<th>Disease</th>
<th>Multicenter or Single Center</th>
<th>Treatment-Related Deaths/Patients, No. (%)</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saccardi et al,(^\text{30}) 2006</td>
<td>MS(^\text{i})</td>
<td>Multiple</td>
<td>10/178 (5.7)(^\text{f})</td>
<td>63% improvement or stabilization</td>
</tr>
<tr>
<td>De Kleer et al,(^\text{34}) 2004</td>
<td>JIA</td>
<td>Multiple</td>
<td>3/34 (9)</td>
<td>53% complete remission</td>
</tr>
<tr>
<td>Farge et al,(^\text{35}) 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,(^\text{35}) 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,(^\text{36}) 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.

\(^{a}\)Excludes reports having <4 patients, reports with multiple autoimmune diseases, and results included in interim or substudy analyses.

\(^{b}\)Nonmyeloablative regimens include combinations of cyclophosphamide, fludarabine, or antilymphocyte antibodies.


\(^{e}\)Progression-, relapse-, and mortality-free survival.

\(^{f}\)Two patients received a myeloablative regimen.

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

\(^{h}\)Not categorized as secondary or primary progressive.

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

\(^{j}\)Does not include 2 cases of late radiation-induced myelodysplastic syndrome/leukemia.

\(^{k}\)One case of late radiation-induced myelodysplastic syndrome/leukemia included in mortality.

\(^{l}\)Includes primary and secondary progressive, relapsing progressive, and relapsing-remitting multiple sclerosis.

\(^{m}\)Transplant-related mortality lower with less intense regimens.
MDS/leukemia, an occurrence consistent with the approximately 10% incidence of MDS after autologous HSCT using total body irradiation regimens in low-grade lymphomas.

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 rATG. 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.

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. 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).

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. Two studies of nonmyeloablative regimens demonstrated 0% (0/10) and 4% (1/26) rates of treatment-related mortality, respectively, while a study using a myeloablative approach including total body irradiation reported a rate of 23% (8/34). Both myeloablative and nonmyeloablative 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. High-intensity myeloablative regimens including total body irradiation or busulfan demonstrated high mortality (including MDS/leukemia), 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. 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. 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.

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).

For rheumatoid arthritis, the majority achieved at least a 50% or greater response; demonstrated re-
nerved responsiveness to traditional disease-modifying medications; had reduction in the rate of joint damage for at least 2 years after transplantation42; and, when compared with baseline, had improvement on health status assessment questionnaires for at least 5 years.43 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).43

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,44 relapsing polychondritis,45 autoimmune-related retinopathy, 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,46 celiac disease,47 polyarteritis nodosa,48 neurovascular Behcet disease,49 neurovascular Sjogren syndrome,50 Takayasu arteritis,51 and Wegner granulomatosis.52 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.49-52 Because it changes genetic predispersion 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 immunemiated 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 data46,49,53 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.54 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.55,56 In nonrandomized trials, 94% of patients with acute GVHD responded to intravenous infusion of MSCs.56

### 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 nonmalignant, 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>
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<td>Systemic sclerosis</td>
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<td><a href="http://www.clinicaltrials.gov">http://www.clinicaltrials.gov</a></td>
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<td>Europe</td>
<td>Pending</td>
</tr>
<tr>
<td>ASTIS</td>
<td>Systemic sclerosis</td>
<td>Europe</td>
<td><a href="http://www.astistrial.com">http://www.astistrial.com</a></td>
</tr>
<tr>
<td>KISS</td>
<td>Crohn disease</td>
<td>United States</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><a href="http://www.clinicaltrials.gov">http://www.clinicaltrials.gov</a></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(NCT00271947)</td>
</tr>
<tr>
<td>MIST</td>
<td>Multiple sclerosis</td>
<td>United States/Canada/Brazil</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><a href="http://www.clinicaltrials.gov">http://www.clinicaltrials.gov</a></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(NCT00273364)</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; ASTMS, Autologous Stem Cell Transplantation International Multiple Sclerosis; ASTIS, Autologous Stem Cell Transplantation International Scleroderma; KISS, Crohn’s Immune Suppression vs Stem Cells; MIST, Multiple Sclerosis International Stem Cell Transplant; SCOT, Scleroderma Cyclophosphamide Or Transplantation; URL, uniform resource locator.**
Clinical Trials of Stem Cell Therapy for Acute Myocardial Infarction With ≥30 Patients

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 Stem Cell Source</th>
<th>Stem Cell Source</th>
<th>LVEF Outcome, Treatment/Control; Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choi et al, 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, 2007</td>
<td>MAGIC Cell 1</td>
<td>30</td>
<td>NA(^a)</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, 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>Tatsumi et al, 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, 2006</td>
<td>Randomized</td>
<td>67</td>
<td>1-2</td>
<td>4</td>
<td>Placebo</td>
<td>Bone marrow</td>
<td>Improved 3.3%/2.2% reduced infarct size (NS)</td>
</tr>
<tr>
<td>Kang et al, 2006</td>
<td>MAGIC Cell-3-DES</td>
<td>82</td>
<td>NA</td>
<td>6</td>
<td>Acute MI/old MI/untreated</td>
<td>Peripheral blood</td>
<td>Improved 5.1%–0.2%</td>
</tr>
<tr>
<td>Lunde et al, 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, 2006</td>
<td>BOOST</td>
<td>60</td>
<td>4.8(^b)</td>
<td>18</td>
<td>None</td>
<td>Bone marrow</td>
<td>Improved 5.9%/5.1% (NS)</td>
</tr>
<tr>
<td>Mansour et al, 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>Meluzin et al, 2006</td>
<td>Randomized(^c)</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, 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, 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, 2006</td>
<td>BOOST</td>
<td>59</td>
<td>4.5(^b)</td>
<td>18</td>
<td>None</td>
<td>Bone marrow</td>
<td>Improved diastolic function (NS)</td>
</tr>
<tr>
<td>Bartunek et al, 2005</td>
<td>Unblinded</td>
<td>35</td>
<td>11.6(^c)</td>
<td>4</td>
<td>None</td>
<td>CD133</td>
<td>Improved/increased infarct-related artery restenosis</td>
</tr>
<tr>
<td>Chen et al, 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, 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, 2004</td>
<td>BOOST</td>
<td>60</td>
<td>4.8(^d)</td>
<td>6</td>
<td>None</td>
<td>Bone marrow</td>
<td>Improved 0.7%/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.

\(^a\)Study assessed both acute and old MI.
\(^b\)Mean value.
\(^c\)Randomized to high-dose, low-dose, or no cells.
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 transplant 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. 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.

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
BLOOD- AND MARROW-DERIVED STEM CELLS FOR NONMALIGNANT DISEASES

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 thrombogenic 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 transcutaneous oxygen pressure improved significantly 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>
<thead>
<tr>
<th>Table 4. Clinical Trials of Stem Cell Therapy for Chronic Myocardial Ischemia and/or Heart Failure With ≥20 Patients</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Source</strong></td>
</tr>
<tr>
<td>Assmus et al.,* 2007</td>
</tr>
<tr>
<td>Losordo et al.,* 2007</td>
</tr>
<tr>
<td>Manginas et al.,* 2007</td>
</tr>
<tr>
<td>Stamm et al.,* 2007</td>
</tr>
<tr>
<td>Assmus et al.,* 2006</td>
</tr>
<tr>
<td>Beeres et al.,* 2006</td>
</tr>
<tr>
<td>Chen et al.,* 2006</td>
</tr>
<tr>
<td>Fuchs et al.,* 2006</td>
</tr>
<tr>
<td>Gao et al.,* 2006</td>
</tr>
<tr>
<td>Hendriks et al.,* 2006</td>
</tr>
<tr>
<td>Mocini et al.,* 2006</td>
</tr>
<tr>
<td>Erbs et al.,* 2005</td>
</tr>
<tr>
<td>Patel et al.,* 2005</td>
</tr>
<tr>
<td>Strauer et al.,* 2005</td>
</tr>
<tr>
<td>Perin et al.,* 2004</td>
</tr>
<tr>
<td>Perin et al.,* 2003</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.

*Control group refused treatment with bone marrow-derived cells.

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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.

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REFERENCES


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