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

Richard K. Burt, MD
Yvonne Loh, MD
William Pearce, MD
Nirat Beohar, MD
Walter G. Barr, MD
Robert Craig, MD
Yanting Wen, MD
Jonathan A. Rapp, MD
John Kessler, MD

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- and xenogeneic-free culture methods approved by the US Food and Drug Administration are still being per-

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.

JAMA. 2008;299(8):925-936

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.

JAMA. 2008;299(8):925-936

©2008 American Medical Association. All rights reserved.

Author Affiliations are listed at the end of this article. Corresponding Author: Richard K. Burt, MD, Division of Immunotherapy, Department of Medicine, Northwestern University Feinberg School of Medicine, 750 N Lake Shore Dr, Room 649, Chicago, IL 60611 (rburt@northwestern.edu).
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 colony-forming unit fibroblasts become adherent cells were originally termed colony-forming unit fibroblasts because they formed fibroblast-like colonies ex vivo. 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. The ratio of MSCs to marrow mononuclear cells is estimated to be only 10 MSCs per million marrow cells.

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.

**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 recurred 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, Wegener’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...
vascular disease, 6 on peripheral vascular disease, 4 on autoimmune disorders, and 26 on autoimmune disorders 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—indeed—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

### Table 1. Treatment-Related Mortality Following Autologous Hematopoietic Stem Cell Transplantation for Autoimmune Diseases

<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><strong>Nonmyeloablative Regimen</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Burt <strong>et al</strong>2005</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 <strong>et al</strong></td>
<td>Crohn disease</td>
<td>Single</td>
<td>0/21 (0)</td>
<td>100% remission; 33% relapse</td>
</tr>
<tr>
<td>Oyama <strong>et al</strong></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 <strong>et al</strong></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 <strong>et al</strong></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>Vonk <strong>et al</strong></td>
<td>Systemic sclerosis</td>
<td>Multiple</td>
<td>1/26 (4)</td>
<td>64% event-free survival at 5 y</td>
</tr>
<tr>
<td>Burt <strong>et al,2006</strong></td>
<td>Secondary progressive MS</td>
<td>Single</td>
<td>1/50 (2)</td>
<td>50% disease-free survival at 5 y</td>
</tr>
<tr>
<td>Snowden <strong>et al,2004</strong></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><strong>Total</strong></td>
<td></td>
<td></td>
<td>2/220 (&lt;1)</td>
<td></td>
</tr>
<tr>
<td><strong>Low-Intensity Myeloablative Regimen</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al-toma <strong>et al,2007</strong></td>
<td>Celiac</td>
<td>Single</td>
<td>0/7 (0)</td>
<td>NA</td>
</tr>
<tr>
<td>Ni <strong>et al,2006</strong></td>
<td>Progressive MS</td>
<td>Single</td>
<td>2/21 (9.5)</td>
<td>42% progression-free survival at 42 mo</td>
</tr>
<tr>
<td>Xu <strong>et al,2006</strong></td>
<td>Secondary progressive MS</td>
<td>Single</td>
<td>0/22 (0)</td>
<td>77% progression-free survival</td>
</tr>
<tr>
<td>Capello <strong>et al,2005</strong></td>
<td>MS</td>
<td>Single</td>
<td>0/21 (0)</td>
<td>20 improved or stable</td>
</tr>
<tr>
<td>Carreras <strong>et al,2003</strong></td>
<td>MS</td>
<td>Single</td>
<td>0/14 (0)</td>
<td>3 improved</td>
</tr>
<tr>
<td>Fassas <strong>et al,2002</strong></td>
<td>Progressive MS</td>
<td>Single</td>
<td>1/24 (4)</td>
<td>78% improved or stabilized</td>
</tr>
<tr>
<td>Kozák <strong>et al,2000</strong></td>
<td>Secondary progressive MS</td>
<td>Single</td>
<td>0/8 (0)</td>
<td>3 improved</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>3/197 (&lt;2)</td>
<td></td>
</tr>
<tr>
<td><strong>High-Intensity Myeloablative Regimen</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nash <strong>et al,2007</strong></td>
<td>Systemic sclerosis</td>
<td>Multiple</td>
<td>8/34 (23)</td>
<td>64% progression-free survival at 5 y</td>
</tr>
<tr>
<td>Samijin <strong>et al,2006</strong></td>
<td>Secondary progressive MS</td>
<td>Single</td>
<td>1/14 (7)*</td>
<td>64% 3-y disease progression</td>
</tr>
<tr>
<td>Burt <strong>et al,2005</strong></td>
<td>Secondary progressive MS</td>
<td>Single</td>
<td>1/21 (5)*</td>
<td>38% progression in 2 y</td>
</tr>
<tr>
<td>Nash <strong>et al,2003</strong></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 <strong>et al,2000</strong></td>
<td>Secondary progressive MS</td>
<td>Single</td>
<td>2/5 (40)</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>13/100 (13)</td>
<td></td>
</tr>
<tr>
<td><strong>Mixed Myeloablative and Nonmyeloablative Regimens</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daiker <strong>et al,2007</strong></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 <strong>et al,2006</strong></td>
<td>MS</td>
<td>Multiple</td>
<td>10/178 (5.9)*</td>
<td>63% improvement or stabilization</td>
</tr>
<tr>
<td>De Kleer <strong>et al,2004</strong></td>
<td>JIA</td>
<td>Multiple</td>
<td>3/34 (9)</td>
<td>53% completion remission</td>
</tr>
<tr>
<td>Farge <strong>et al,2004</strong></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 <strong>et al,2004</strong></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 <strong>et al,2001</strong></td>
<td>Systemic sclerosis</td>
<td>Multiple</td>
<td>7/41 (17)</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Total</strong></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 sub-study 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.

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

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 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. 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 regimens 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 15 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-
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">http://www.clinicaltrials.gov</a> (NCT00114530)</td>
</tr>
<tr>
<td>ASTIL</td>
<td>Systemic lupus erythematosus</td>
<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><a href="http://www.clinicaltrials.gov">http://www.clinicaltrials.gov</a> (NCT00271947)</td>
</tr>
<tr>
<td>MIST</td>
<td>Multiple sclerosis</td>
<td>United States/Canada/Brazil</td>
<td><a href="http://www.clinicaltrials.gov">http://www.clinicaltrials.gov</a> (NCT00273364)</td>
</tr>
</tbody>
</table>

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, Crohn Immune Suppression vs Stem Cells; MIST, Multiple Sclerosis International Stem Cell Transplant; SCOT, Scleroderma Cyclophosphamide Or Transplantation; URL, uniform resource locator.

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 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-
isms remain controversial, a substantial number of clinical trials have been initiated using BMMCs, 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 BMMCs, 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 BMMCs with that of CPCs.\(^ {74-77}\) BMMCs 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 BMMCs with placebo 3 to 7 days after successful percutaneous coronary intervention and demonstrated improved recovery of left ventricular contractility in the cell treatment group.\(^ {98}\) 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 BMMCs significantly improved LVEF 6 months after intracoronary transplantation.\(^ {40}\) 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 \(\geq 30\) 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,(^ {71}) 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,(^ {58}) 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,(^ {72}) 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,(^ {73}) 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>Janseins et al,(^ {62}) 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,(^ {60}) 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(^ {53}) 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,(^ {61}) 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%/–3.1% (NS)</td>
</tr>
<tr>
<td>Mansour et al,(^ {62}) 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>Melzin et al,(^ {71}) 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,(^ {58}) 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%/2.0%</td>
</tr>
<tr>
<td>Schächinger et al,(^ {58}) 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>Schafer et al,(^ {62}) 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,(^ {60}) 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,(^ {68}) 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,(^ {57}) 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,(^ {60}) 2004</td>
<td>BOOST</td>
<td>60</td>
<td>4.8(^ b)</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.

\(^{a}\)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 benefi
cial effects from intracoronary transplant-
lation of BMMCs on LVEF. Compared with controls, BMMCs tended to improve LVEF as demon-
strated 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 sig-
ificantly different.

The MAGIC (Myocardial Regeneration
and Angiogenesis in Myocardial In-
farction With G-CSF and Intracoronary
Cell Infusion) Cell 1 study com-
pared intracoronary transplant of granu-
locyte colony–stimulating factor (G-
CSF)–mobilized PBSCs vs treatment with
G-CSF alone vs an untreated control
group.64 Left ventricular ejection frac-
tion improved in the PBSC group com-
pared with the G-CSF-alone group, and
there was an increase in restenosis in pa-
ients receiving G-CSF. The subsequent
MAGIC Cell-3-DES (Myocardial Regen-
eration and Angiogenesis in Myocardial
Infarction With G-CSF and Intracoroni-
ary Stem Cell Infusion-3-Drug Eluting Stents) study compared intra-
coronary transplantation of G-CSF-
mobilized PBSCs vs an untreated con-
trol group.65 Left ventricular ejection frac-
tion and remodeling improved com-
pared with controls in the cell-treated
group.65,78

Significant improvement in LVEF
has been reported following injection of
MSCs as well as of BMMCs, CPCs, and
PBSCs.80

Taken as a whole, the results of in-
tracoronary transplantation of progeni-
tor cells following ST-segment eleva-
tion acute myocardial infarction are
generally viewed as conveying a mod-
est 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. In-
terstudy and intrastudy reproducibil-
ity of LVEF demonstrated by echocar-
diography and cardiovascular magnetic
resonance imaging varies signifi-
cantly, with conservative estimates
of 8.6% and 2.4%, respectively.80 Repro-
ducibility of LVEF measurement,
therefore, over laps with anticipated im-
provement (2%-5%) from stem cell
transplantation. Nevertheless, 3 sepa-
rate meta-analyses of controlled clini-
cal trials of stem cell therapy in acute
myocardial infarction have indicated
modest benefit.81-83

Chronic Coronary Artery Disease.
In chronic ischemic cardiac disease or old
myocardial infarction, noncontracting
but viable myocardium, termed hiber-
nating myocardium, is a physiologic re-
sponse to hypoxic stress that halts the en-
ergy demands of contraction to prevent
cardiomyocyte death. In the laboratory,
hibernating myocardium is identified by
areas of electromechanical dissociation,
ies myocardium that conducts elec-
tricity but does not contract.

Initial trials using stem cells in old
myocardial infarction or chronic ische-
ia involved thoracotomy and coro-
ary artery bypass graft surgery with
simultaneous epicardial-directed intra-
myocardial injection of BMMCs or
PBSCs while the heart was still arrested
during cardiopulmonary bypass. Subse-
quent, most patients with chronic ische-
mic heart disease received stem cells
by either percutaneous intracoronary or
endomyocardial delivery without under-
going simultaneous coronary artery by-
pass graft surgery.84-86 (Table 4). Erbs
et al84 treated chronic (>30-day) total coro-
nary occlusion with recanalization, fol-
lowed 10 days later by randomization to
intracoronary CPC infusion or no cells.
Patients receiving CPCs had significant
improvement in LVEF. In the IACT (In-
tracoronary Autologous Bone Marrow
Cell Transplantation in Chronic Coro-
nary Artery Disease) trial, Strauer et al85
treated old myocardial infarction (5
months to 8.5 years prior) with intra-
coronary BMMCs, with significant
improvement in LVEF. Assmus et al86
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;86 if heart fail-
ure was present, injection of BMMCs re-
sulted in significant reduction of brain
natriuretic peptide, a serum marker for
heart failure.87

In summary, pump failure has been
a historically vexing problem and, de-
spite maximizing medical therapy, of-
ten progressive and irreversible. Sym-
ptomatic relief of pain may be a placebo
effect. Nevertheless, stem cell treat-
ment of chronic myocardial ischemia
has generally been reported to in-
crease regional perfusion, wall mo-
tion, and global LVEF; and to relieve an-
gina pectoris. A recent meta-analysis
reported a modest association be-
tween blood- or marrow-derived stem
 cell injection and improvement in
chronic ischemic heart disease.81

Peripheral Vascular Disease. Tis-
tue limb ischemia from peripheral vas-
cular disease usually manifests in the
lower extremities and may be due to
thromboangiitis obliterans (Buerger dis-
 ease) or atherosclerosis obliterans. The
mainstay of treatment for peripheral
vascular disease has been surgical re-
vascularization. Patients with critical
limb ischemia that have exhausted op-
erative revascularization procedures
are traditionally treated by limb ampu-
tation. 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 mar-
row 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 proce-
dure has generally been performed safely,
although 1 case of an arteriovenous fis-
tula at the injection site has been re-
ported.102 While most investigators pre-
fer percutaneous injection into the

932 JAMA, February 27, 2008—Vol 299, No. 8 (Reprinted) ©2008 American Medical Association. All rights reserved.
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. In contrast, depending on the report, approximately two-thirds (70%) of patients with atherosclerosis obliterans responded.

The TACT (Therapeutic Angiogenesis by Cell Transplantation) trial enrolled patients with bilateral (n=22) or unilateral (n=25) peripheral vascular disease. 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. The group receiving BMMCs (n=13) had significantly improved pain-free walking time, ankle-brachial index, and capillary-venous oxygen saturation.

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. 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.

**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 regimes are used, indicating the need for development of safer myeloablative 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</th>
<th>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, 2007</td>
<td>TOPCARE-CHD</td>
<td>121</td>
<td>19</td>
<td>Intracoronary</td>
<td>Bone marrow</td>
<td>Improved mortality in high-order CFUs injected</td>
</tr>
<tr>
<td>Losordo et al, 2007</td>
<td>Randomized</td>
<td>24</td>
<td>12</td>
<td>Intramyocardial</td>
<td>CD34</td>
<td>Not examined</td>
</tr>
<tr>
<td>Manginas et al, 2007</td>
<td>Unblinded</td>
<td>24</td>
<td>28</td>
<td>Intracoronary</td>
<td>CD133, CD34</td>
<td>Improved LVEF and left ventricular volumes</td>
</tr>
<tr>
<td>Stamm et al, 2007</td>
<td>Unblinded</td>
<td>40</td>
<td>6</td>
<td>Intramyocardial</td>
<td>CD133</td>
<td>Improved LVEF</td>
</tr>
<tr>
<td>Assmus et al, 2006</td>
<td>TOPCARE-CHD</td>
<td>75</td>
<td>3</td>
<td>Intracoronary</td>
<td>Bone marrow/ CPCs</td>
<td>Improved with bone marrow</td>
</tr>
<tr>
<td>Beeres et al, 2006</td>
<td>Single group</td>
<td>25</td>
<td>12</td>
<td>Intramyocardial</td>
<td>Bone marrow</td>
<td>Improved LVEF, CCS angina score, perfusion</td>
</tr>
<tr>
<td>Chen et al, 2006</td>
<td>Unblinded</td>
<td>45</td>
<td>12</td>
<td>Intracoronary</td>
<td>Mesenchymal</td>
<td>Improved ischemia, NYHA class, and LVEF</td>
</tr>
<tr>
<td>Fuchs et al, 2006</td>
<td>Single group</td>
<td>27</td>
<td>12</td>
<td>Intramyocardial</td>
<td>CD34</td>
<td>Improved CCS angina score</td>
</tr>
<tr>
<td>Gao et al, 2006</td>
<td>Unblinded</td>
<td>28</td>
<td>3</td>
<td>Intracoronary</td>
<td>Bone marrow</td>
<td>Improved LVEF, improvement in CHF</td>
</tr>
<tr>
<td>Hendriks et al, 2006</td>
<td>Randomized</td>
<td>20</td>
<td>4</td>
<td>Intramyocardial</td>
<td>Bone marrow</td>
<td>NS</td>
</tr>
<tr>
<td>Mocini et al, 2006</td>
<td>CABG + cells or CABG alone</td>
<td>36</td>
<td>12</td>
<td>Intramyocardial</td>
<td>Bone marrow</td>
<td>Improved LVEF and wall motion</td>
</tr>
<tr>
<td>Erbs et al, 2005</td>
<td>Randomized</td>
<td>26</td>
<td>3</td>
<td>Intracoronary</td>
<td>CPCs</td>
<td>Improved</td>
</tr>
<tr>
<td>Patel et al, 2005</td>
<td>Randomized</td>
<td>20</td>
<td>6</td>
<td>Intramyocardial</td>
<td>CD34</td>
<td>Improved</td>
</tr>
<tr>
<td>Strauer et al, 2005</td>
<td>IACT A</td>
<td>36</td>
<td>3</td>
<td>Intracoronary</td>
<td>Bone marrow</td>
<td>Improved</td>
</tr>
<tr>
<td>Perin et al, 2004</td>
<td>Sequential enrollment; treatment or control</td>
<td>20</td>
<td>12</td>
<td>Intramyocardial</td>
<td>Bone marrow</td>
<td>NS</td>
</tr>
<tr>
<td>Perin et al, 2003</td>
<td>Single group</td>
<td>21</td>
<td>4</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.

AControl group refused treatment with bone marrow-derived cells.

(Reprinted) JAMA, February 27, 2008—Vol 299, No. 8
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.\(^{109,111}\)

**REFERENCES**


BLOOD- AND MARROW-DERIVED STEM CELLS FOR NONMALIGNANT DISEASES


74. Erbs S, Linke A, Adams V, et al. Transplantation...


