Bone Marrow Mononuclear Cell Therapy for Acute Myocardial Infarction

A Perspective From the Cardiovascular Cell Therapy Research Network


Abstract—To understand the role of bone marrow mononuclear cells in the treatment of acute myocardial infarction, this overview offers a retrospective examination of strengths and limitations of 3 contemporaneous trials with attention to critical design features and provides an analysis of the combined data set and implications for future directions in cell therapy for acute myocardial infarction. (Circ Res. 2014;114:1564-1568.)

Key Words: diagnostic imaging • myocardial infarction • population

Recent meta-analyses of cell therapy clinical trials have suggested that bone marrow mononuclear cell (BMC) delivery after acute myocardial infarction (AMI) may result in modest improvement in left ventricular (LV) function.1 Despite this, the uniformly null findings emerging from the most current trials, Transplantation In Myocardial infarction Evaluation (TIME),2 LateTIME,3 and Swiss Multicenter Intracoronary Stem Cells Study in Acute Myocardial Infarction (SWISS-AMI),4 have prompted careful reconsideration of this approach.

Background
By late 2006, multiple preclinical models of AMI suggested that the delivery of BMC-derived cells improved LV function after AMI.5,6 Although the original study by Orlic et al7 suggested transdifferentiation as the mechanism of action, this was not confirmed by others.7,8 However, the study by Balsam et al9 demonstrated functional benefits despite failing to provide data supporting transdifferentiation. It is thought that BMCs might have pleiotropic and diverse effects in this setting, including stimulating angiogenesis and other paracrine effects.9 These findings fueled intense interest in assessing the effects of autologous BMC delivery on LV function in clinical trials.10-13 Although initial studies showed somewhat mixed results, meta-analyses supported a significant effect of intracoronary delivery of BMCs on LV ejection fraction (LVEF). Three points are important to note. (1) These trials varied widely in design and subject characteristics. (2) None of these meta-analyses used patient-level data. (3) The trial responsible for driving the perceived benefit was Reinfusion of Enriched Progenitor Cells and Infarct Remodeling in Acute Myocardial Infarction (REPAIR-AMI),10 the largest (n=204) trial reported by 2006, with ≥2-fold difference in LVEF improvement in the active group versus placebo and nonrandomly allocated assignment of time of cell delivery. The Cardiovascular Cell Therapy Research Network (CCTRN) was designed to execute multiple, simultaneous cell therapy protocols in the clinical setting of LV dysfunction.14 After consideration, the investigators decided to test the effect of timing of administration of BMCs while using standard approaches to other features of trial design common to other studies.

Although a prespecified variable in REPAIR-AMI, the timing of cell delivery was not subject to randomization in it or earlier studies. Thus, the TIME and LateTIME trials were initiated to study the impact of timing of BMC delivery after AMI. During the same time period, Swiss investigators, working independently, also decided to focus on timing of BMC administration after AMI (SWISS-AMI).15 TIME evaluated cell delivery at day 3 or day 7 after reperfusion (primary percutaneous coronary intervention [PCI] with stenting); LateTIME evaluated cell delivery 2 to 3 weeks postreperfusion; and SWISS-AMI compared the effects of delivery on days 5 to 7 versus 3 to 4 weeks post-PCI (Figure 1).

From Mayo Clinic, Rochester, MN (R.D.S., D.B.S.); University of Florida School of Medicine, Gainesville (C.J.P., R.D.A.); Minneapolis Heart Institute at Abbott Northwestern Hospital, University of Minnesota School of Medicine (J.H.T.); Cedars-Sinai Heart Institute, Los Angeles, CA (T.D.H.); University of Louisville School of Medicine, KY (R.B.); The University of Texas MD Anderson Cancer Center, Houston (E.Y.); University of Miami Miller School of Medicine, FL (J.M.H., I.H.S.); Florida Hospital Tampa Pepin Heart Institute (C.L.); University of Texas Health Science Center School of Public Health, Houston (S.L.S., L.A.M.); Texas Heart Institute, Houston (D.A.T.); and National Heart, Lung, and Blood Institute, Bethesda, MD (R.F.E.).

This article was sent to Gordon Tomaselli, Consulting Editor, for review by expert referees, editorial decision, and final disposition.

The online-only Data Supplement is available with this article at http://circres.ahajournals.org/lookup/suppl/doi:10.1161/CIRCRESAHA.114.303720/-/DC1.

Correspondence to Lemuel A. Moyé, MD, PhD, Coordinating Center for Clinical Trials, University of Texas School of Public Health, 1200 Herman Pressler, E-1009, Houston, TX 77030. E-mail Lemmoye@msn.com

© 2014 American Heart Association, Inc.
Circulation Research is available at http://circres.ahajournals.org

DOI: 10.1161/CIRCRESAHA.114.303720
Internal Consistency of TIME, LateTIME, and SWISS-AMI

TIME, LateTIME, and SWISS-AMI were contemporaneous, prospective, randomized, controlled trials. TIME and LateTIME recruited predominantly ST-segment-elevation myocardial infarction and were both placebo-controlled and double-blind design; SWISS-AMI recruited exclusively ST-segment-elevation myocardial infarctions but did not have placebo controls and was an open design and used LV angiograms post-PCI to qualify subjects. The primary end points focused on global LVEF measured by cardiac magnetic resonance (cMR) imaging, but the timing of this was different (TIME/LateTIME at 6 months and SWISS-AMI at 4 months). Intention-to-treat analyses were conducted in each study. Each was designed to detect moderate to large placebo-adjusted changes in LVEF. Randomizations were 2:1 (active:placebo) in both TIME and LateTIME and 1:1:1 in SWISS-AMI. Cell processing was by manual Ficoll processing at a central center in SWISS-AMI, whereas the 2 CCTRN studies used onsite automated Ficoll processing (SEPAX; Biosafe, SA). Cell dose and delivery were the same in each of these 3 studies using the intracoronary stop-flow technique. Although differences did exist between the 2 studies (in SWISS-AMI, there was an open design, use of LV angiography immediately post-PCI for qualification of subjects, no requirement of primary PCI or stents in eligible patients, and central cell processing requiring >24-hour delayed delivery of BMC), the similarities suggested that a comparison of their results would be productive.

Overall, the primary results for TIME, LateTIME, and SWISS-AMI were each null with no detectable benefit of cell therapy evident when administered at day 3, day 7, 2 to 3 weeks, or 3 to 4 weeks post-PCI. Thus, despite previous clinical studies and recent meta-analyses supporting an effect of BMC delivery on echocardiogram-derived LV function post-AMI, these 3 studies did not detect a significant treatment effect on LV function. The evaluation of clinical end points revealed no safety concerns, but the intracoronary administration of BMCs did not improve LV function after AMI irrespective of the timing of administration.

Variables Addressed in These Studies

Study Population

Because compelling work from the REPAIR-AMI trial suggested that patients with AMI with the greatest impairment of LVEF seemed to gain the most benefit from BMC therapy, the CCTRN chose to study patients with infarctions resulting in an LVEF of <45% after successful reperfusion by PCI. Given the need to randomize patients in TIME by day 2, local echocardiographic readings were used to screen patients, whereas baseline and end point values were determined by core laboratory assessment of cMR imaging. In TIME and LateTIME, these qualifying echocardiograms, which were obtained closer in time to reperfusion than the following baseline cMRs, revealed lower LVEF compared with baseline cMR (Figure 2A), resulting in the inclusion of a population with less LV dysfunction than proposed. As a result, a significant part of our patient population in both TIME and LateTIME had less LV dysfunction (as measured by cMR) than anticipated. Reducing the threshold for enrollment, to say LVEF ≤ 40%, or obtaining screening core cMR closer to the time of delivery are admissible alternatives for future trials, although each comes with greater logistical challenges, financial cost, and risks to timely recruitment.

In SWISS-AMI that randomized subjects to early treatment (5–7 days), late treatment (3–4 weeks), or control, patients were screened by LV angiogram or echocardiography (<45%) the day of or after AMI. The median baseline LVEF was 37% by cMR. The delivery of BMCs demonstrated no benefit.

Nonstandard Abbreviations and Acronyms

<table>
<thead>
<tr>
<th>Nonstandard Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMI</td>
<td>acute myocardial infarction</td>
</tr>
<tr>
<td>BMC</td>
<td>bone marrow mononuclear cell</td>
</tr>
<tr>
<td>CCTRN</td>
<td>Cardiovascular Cell Therapy Research Network</td>
</tr>
<tr>
<td>cMR</td>
<td>cardiac magnetic resonance</td>
</tr>
<tr>
<td>LV</td>
<td>left ventricular</td>
</tr>
<tr>
<td>LVEF</td>
<td>left ventricular ejection fraction</td>
</tr>
<tr>
<td>PCI</td>
<td>percutaneous coronary intervention</td>
</tr>
</tbody>
</table>

Figure 1. Placebo-adjusted effect size for change in left ventricular ejection fraction (LVEF) over time as a function of time from primary percutaneous coronary intervention (PCI) in 4 clinical trials. The upper and lower bar limits reflect the upper and lower confidence interval of the effect size; the bar width is proportional to the sample size. REPAIR-AMI indicates Reinfusion of Enriched Progenitor Cells and Infarct Remodeling in Acute Myocardial Infarction; SWISS-AMI, Swiss Multicenter Intracoronary Stem Cells Study in Acute Myocardial Infarction; and TIME, Transplantation In Myocardial infarction Evaluation.
despite the greater baseline degree of dysfunction. Thus, we think that it is unlikely that the degree of baseline LV dysfunction was a major reason for the null results.

In the face of these null findings for LVEF, power becomes a critical factor. SWISS-AMI was powered to detect a 3.5 (absolute LVEF unit) placebo-adjusted change (>4 months) in EF. TIME was powered to detect a 5-unit placebo-adjusted change (>6 months). Although TIME and LateTIME were adequately powered overall, the sample sizes in LVEF \( \leq 40 \) subgroups were too small and underpowered to detect these same effect sizes.

The planned similarities between TIME and LateTIME permit the opportunity to conduct additional evaluation of the combined data sets. An analysis was completed using a data set containing 81 of 87 patients from LateTIME, and 112 of 120 patients from TIME, all of whom had paired cMR LV images at baseline and 6 months. We observed no overall effect of BMC therapy on the change in LVEF over time (placebo-adjusted change in LVEF, \(-1.4 \pm 9.5; P=0.967; 95\% \text{ confidence interval}, -0.34 \text{ to } -0.10\); Figure 2B). This effect remained after adjusting for age and time from PCI to infusion. Neither age nor time from PCI to cell infusion (days) had a significant relationship with change in LVEF from baseline to 6 months in either study or the combined data set as was the case in SWISS-AMI.\(^4\) These analyses suggest but do not prove that the greatest change in LVEF during the study period occurs in the cohort with the most severe baseline LV dysfunction.

**Size of the Study Population**

In view of the results, questions have been raised about the size and power of these studies. These 3 trials were powered to detect placebo-adjusted LVEF increases from 3.5\% to 5\%. Great variability and heterogeneity across clinical centers all but preclude identifying small effect sizes. However, we did not anticipate the small effect sizes that we observed. These miniscule effects were not presaged by the literature, which instead reported (eg, REPAIR-AMI) much larger effects of cell therapy. Presuming that these moderate to large effects would be discoverable in our trials, we focused on whether the timing of administration of cells would influence these

---

**Figure 2.** A, Relationship between the baseline left ventricular ejection fraction (LVEF) MRI–based assessment and the screening echocardiographic (echo)–based LVEF. The correlation is substantial, and in general the core laboratory assessment is greater than the echo-based assessment. B, Relationship between change in LVEF over time and baseline EF in the TIME and LateTIME trials. On average, the greater the baseline LVEF, the smaller the increase in LVEF from baseline to 6 mo. cMR indicates cardiac magnetic resonance; and TIME, Transplantation In Myocardial infarction Evaluation.
effects. In addition, these effect sizes were beyond the ability of clinical centers to measure with requisite precision.

Additionally, smaller study sizes may result in incomplete randomization of baseline variables as was the case in these studies. Additionally, and perhaps unexpectedly, the randomization to different delivery times affected the study populations. The intended delay between enrollment and delivery resulted in greater numbers of patients withdrawing from the studies from groups that received delivery at later time points. Thus, considerations balancing the costs of larger trials and the inherent uncertainty of smaller trials are critical to the field of cell therapy. Furthermore, in trials of AMI in which subjects need to return to the hospital after discharge, designs need to account for the possibility of withdrawal of subjects once discharged.

Randomization Models
In CCTRN studies, a 2:1 ratio of BMC-treated subjects to placebo was used to balance the rigor of the study with the need to recruit subjects to a trial that required BM harvest and invasive delivery of cells. However, in addition to reducing statistical power, it also generated a placebo group 50% smaller than that of an equal randomization model, creating inequalities in the baseline characteristics and increased variability because of small sample sizes in the placebo group. The CCTRN favors designs that include a placebo group as robust as possible for comparisons; in general, the Network endorses equal randomization as was done in SWISS-AMI.

Standardization of Cell Processing
To limit the potential sources of variability related to cell product, the CCTRN adopted distributed and automated cell processing (Sepax; Biosafe) at each of the 5 regional centers as opposed to centralized processing. This decision was based on several lines of reasoning. First, the use of open Ficoll systems for BMC isolation was becoming less standard in the United States with the advent of cell mobilization and isolation for clinical hematopoietic stem cell transplantation. Second, the use of a closed-automated system enabled local preparation and standardization. Despite the striking similarity to the negative results of SWISS-AMI, which used manual Ficoll processing, concerns have been raised about the functionality of the BMC product used in TIME and LateTIME. These included the potential effects of erythrocytes and heparin in the study product. We have presented data to suggest that these concerns are not warranted. Notably, in the First Mononuclear Cells injected in the United States conducted by the CCTRN (FOCUS-CCTRN) trial, with Sepax-processed cells, there was an observed increase in LVEF in the BMC group versus placebo at 6 months in patients with chronic LV dysfunction.

Additional studies performed by the Network compared the effects of human BM separated by Sepax or by manual Ficoll preparation in 2 distinct immunodeficient murine models, hindlimb ischemia, and myocardial infarction. Results of these studies indicate that Sepax and manual Ficoll-isolated cells resulted in similar effects in these complementary models (Online Figure). Although several differences exist that distinguish SWISS-AMI from TIME and LateTIME taken together, the data suggest that the negative results of TIME, LateTIME, and SWISS-AMI are more likely to be because of the inherent nature of BMCs than the means by which they are isolated or stored.

Timing of Cell Harvest and Delivery
The timing of harvest and delivery in SWISS-AMI affected the content of the BM product. CD34 cell content was marginally higher at 3 to 4 weeks than at 5 to 7 days after myocardial infarction (%CD34: 1.31% late, 1.02% early; P=0.01), but this was not seen when comparing cells from TIME and LateTIME. These studies do not support a major impact of timing of cell harvest on BMC product.

End Point Selection
Each study used cMR as the most rigorous method to assess LVEF, whereas TIME and LateTIME used a coprimary end point of regional LV function. CCTRN followed the concept used in Bone Marrow Transfer to Enhance ST-Elevation Infarct Regeneration (BOOST), using wall motion in the infarct zone and border zone. Precision for the assessment of regional LV function was substantially better than for global LV function, suggesting that the sample size for a 2-armed clinical trial is substantially smaller when designed around regional function rather than global LV function.

Future Directions for Cell Therapy After AMI
In 2007, cell therapy clinical trials of BMCs in AMI were considered highly innovative with a growing safety profile and hopes for effects. Despite early positive studies including BOOST, which used cMR as the primary end point, a meta-analysis of studies using LVEF by cMR as the primary end point did not show a statistically significant effect of unfractionated BMCs on LVEF. Why, in aggregate, the studies using echo end points demonstrate differences in LV function assessment whereas those using cMR do not remains an unsettled question.

Early preclinical and clinical trial findings suggested that BMC delivery could improve LV function. This coupled with the strong public demand for new interventional strategies propelled this collection of clinical investigations. Although the impact of BMCs on survival after AMI remains to be determined, there may be a future for incorporation of some aspects of BM-derived cells with selected or enriched populations. However, the promise of a major impact of BMCs on LV function seems unfounded. A potential effect on mortality will be examined in the prospective Bone Acute Myocardial Infarction (BAMI) trial, a phase III trial in Europe aimed to test the hypothesis that BMCs improve 2-year survival after AMI. The CCTRN eagerly awaits the results of BAMI as they will effectively make all of the ongoing discussion surrounding the effects of BMC after AMI on LVEF moot, because the study is purely designed to test the effects on mortality.

Meanwhile, concepts of off-the-shelf cell delivery after AMI with an allogeneic cell (eg, allogeneic mesenchymal stem cells) delivered at multiple doses and timing (even as early as reperfusion) are promising. Another alternative is one in which cells are delivered in the postacute period after the initial phases of recovery and remodeling, which would permit their intramyocardial effect to develop in the presence of stable LV function. This research pathway is lit by a collection of post–myocardial infarction LV dysfunction trials, including FOCUS-CCTRN, POSEIDON (The Percutaneous
Stem Cell Injection Delivery Effects on Neomyogenesis Pilot Study), TAC-HFT (The Transendocardial Autologous Cells [hMSC or hBMC] in Ischemic Heart Failure Trial), SCIPIO (Cardiac Stem Cell Infusion in Patients With Ischemic Cardiomyopathy), CADUCEUS (Cardiosphere-Derived Autologous Stem Cells to Reverse Ventricular Dysfunction), and C-CURE.23–28 Although BMC use in patients with AMI has diminished (at least temporarily), the future of cell therapy for LV dysfunction resulting from AMI remains bright.

Acknowledgments
We acknowledge the contributions of Dr Skarlatis (1953–2013) for his insight, expertise, and support of the Cardiovascular Cell Therapy Research Network, which continues to propel the cell therapy field forward.

Sources of Funding
Funding for the Cardiovascular Cell Therapy Research Network was provided by the National Heart, Lung, and Blood Institute under cooperative agreement UM1 HL087318-07.

Disclosures
None.

References
Bone Marrow Mononuclear Cell Therapy for Acute Myocardial Infarction: A Perspective
From the Cardiovascular Cell Therapy Research Network

Circ Res. 2014;114:1564-1568
doi: 10.1161/CIRCRESAHA.114.303720

Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2014 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7330. Online ISSN: 1524-4571

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circres.ahajournals.org/content/114/10/1564

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation Research can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation Research is online at:
http://circres.ahajournals.org//subscriptions/