Acute myocardial infarction is the most generally accepted cause of morbidity and mortality in developed countries. Despite rapid restoration of perfusion, postinfarction heart failure remains a major challenge. Considerable experimental and clinical evidence indicates the feasibility of therapeutic implantation of bone marrow–derived cells in reversing abnormal cardiac remodeling with the generation of cardiac myocytes, as well as the stimulation of neovascularization within the infarcted area.1–3 Although therapeutic delivery of stem cells following myocardial infarction and heart failure is being explored in clinical trials (see http://www.clinicaltrials.gov for the list of ongoing trials), little is yet known about what determines the fate of stem cells and how they move into and within tissues to provide a regenerative effect. The acute fate of these cells in the microcirculation seems of particular interest, because the small blood vessels are the site of adhesion and migration of circulating cells, including systemically or locally administered stem cells, into the tissues. One would expect that an intimate interaction of stem cells with elements of the microcirculation plays a crucial role in integration and survival of cells, allowing for potential tissue repair.

Among the various cell types investigated, bone marrow–derived mesenchymal stem cells (MSCs) are self-renewing clonal precursors of nonhematopoietic stromal tissues.4,5 MSCs represent a type of adult stem cell that can easily be isolated from various tissues and expanded in vitro.4 Evidence indicates that MSCs give rise to osteoblasts and chondroblasts and that under appropriate conditions, they can also express phenotypic characteristics of endothelial, neural, and smooth muscle cells, as well as skeletal myoblasts and cardiac myocytes.5 The MSCs, with their ease of isolation, high expansion potential and genetic stability, and potential to promote tissue repair, appear to be an appealing source for stem cell therapy, but the lack of common criteria of MSC identity and characteristics, as well as the lack of universal standards for preparation of MSCs, seem to hamper further progress in this field of investigation.6 The low survival rate of MSCs after administration into an ischemic tissue further limits their therapeutic efficacy.7,8 Perhaps, because current imaging techniques used to track implanted stem cells do not allow for direct visualization of individual cells, knowledge of the exact mechanisms responsible for the limited survival of MSCs is still missing.

Ideal imaging technology used for stem cell tracking would have single-cell sensitivity and would permit quantification of cell numbers at any anatomic location. The current imaging techniques, such as x-ray, ultrasound, single-photon emission CT, positron emission tomography, magnetic resonance, and optical imaging, to track stem cells in vivo, are far from ideal.9,10 Thus, the pattern of migration of stem cells even after local administration remains essentially unknown. It would be important to determine the acute fate of stem cells following intravascular administration to be able better to predict their survival to ensure incorporation into the tissue to facilitate regeneration. Although studies have measured MSC survival and apoptosis following their administration,11,12 no studies have examined the time course of cell infiltration through the vascular wall in relationship to cell survival. Also, there is no direct assessment extant of the ability of MSCs to pass through microvascular networks.

Previous studies aimed at following MSC distribution on systemic delivery have shown that most of the cells became entrapped in the lung.5,13 Only a direct injection of MSCs into the ischemic myocardium enhanced migration and colonization of the implanted cells.9 Interestingly, a study by Vulliet et al. showed that intracoronary injection of bone marrow–derived MSCs causes myocardial infarction in a dog model, as indicated by ECG changes, increased troponin I levels, and postmortem histological data.14 Although clinical studies have shown that intracoronary infusion of MSCs at the time of or after myocardial infarction is safe and could be of benefit to patients,3 the aforementioned study raised the possibility that MSCs are easily entrapped in the microcirculation, a phenomenon, the significance of which is unknown.

In this issue of Circulation Research, Toma et al.5 describe an innovative approach that aims to assess the acute fate of intraarterially injected MSCs in the rat cremaster muscle microcirculation. The authors used intravital microscopy to observe cellular migration in this skeletal muscle microcirculation under conditions that preserve the local microvessel architecture. The results show that upon intraarterial injection, most of the in vitro expanded MSCs, whose average diameter was 23 μm, became entrapped in precapillary vessels, resulting in cessation of blood flow in the feeding artery. The majority of the entrapped cells became nonfunctional and exhibited cytoplasmic fragmentation and nuclear condensation. Despite the substantial cell loss, 14% of the surviving cells became integrated into the microvascular wall or were seen at perivascular locations, at a precapillary level, within the 72-hour period of observation, indicating that integration of MSCs occurred at the point of initial entrapment. Based on these results, the authors concluded that on intraarterial delivery only a small proportion of MSCs integrated into the microvascular wall. Thus, they imply that to

Where Have All the Stem Cells Gone?

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enhance therapeutic success, one needs to avoid microembolization, primarily by aiming to retain the original size of MSCs (which is half that of the cells used in this study) during in vitro expansion, while preserving their putative ability for active engraftment.

The authors themselves acknowledge that only a few stem cells survive and integrate into perivascular niches at 3 days. Thus, it is likely that the number of MSCs surviving is far too small to induce a quantifiable angiogenic or regenerative response. In addition, the relative number of integrated MSCs might be overestimated in this case, because the study by Toma at el15 does not exclude the possibility that during the fragmentation of MSCs the remaining fluorescent probe, used to label these cells, can be taken up by and incorporated into the surrounding phagocytes residing in the microvascular wall. This problem could be addressed if the fate of individual cells were to be followed by real time imaging to ensure cell identity during the observation period. Furthermore, in the aforementioned study by Vulliet et al14 and in the present article by Toma et al,15 MSCs were injected intraarterially to perfuse uninjured tissues, i.e., the heart and skeletal muscle of healthy animals. Most likely, because of the larger cell size of MSCs, acute microembolization developed on intraarterial injection, leading promptly to tissue ischemia, although in the present instance, one needs to consider that the cremaster muscle has a low oxygen consumption and therefore tissue injury may only be slight. It should be emphasized that in the study by Toma et al,15 clumping of MSCs itself would cause ischemia and injury to the tissue, whereas in a clinical situation, it is the already distressed tissue, to which the implanted MSCs will be attracted, to exert their paracrine effects, eventuating in tissue repair.2 Various cell culture conditions to reduce the size of MSCs and thus limit the tendency for microembolization, as suggested by the authors, will not necessarily yield a more efficient cell engraftment in the already ischemic tissue. However, it is possible that smaller MSCs would penetrate deeper into the microcirculatory network, especially, if in presence of a vasospasm, vasodilator agents were coadministered with the cells.13 One can also envision that entrapment of the relatively large-sized MSCs at a precapillary level would facilitate their transmigration and integration into tissues. This seems especially important because a large body of evidence indicates that the therapeutic efficacy of MSCs (eg, preservation of myocardial function) is closely related to the number of in situ viable cells implanted into the hostile environment of hypoxic and inflamed tissues.12 In this context, previous studies elegantly demonstrated that genetic modification of MSCs (for instance, overexpression of the prosurvival gene Akt12 or the antiapoptotic gene Bcl-211) enhances survival of the engrafted MSCs in the heart after acute myocardial infarction, resulting in improved cardiac performance.

Collectively, there appears to be a series of both mechanical and biological events, including those described by Toma et al,15 that have to be taken into account when investigating the acute and chronic fate of stem cells in tissue repair processes. Importantly, the impact of these factors should be investigated in a setting similar to clinical conditions. Accordingly, the fate of implanted or infused stem cells should be evaluated in injured tissues, in which the microvascular architecture has deteriorated, as in the infarcted myocardium. Real-time tracking of the implanted stem cells seems also essential; this, however, requires novel imaging techniques, in which intravital microscopy is used to study a preparation that is available for chronic observation. This experimental design would also facilitate evaluation of an angiogenic response and tissue repair initiated by the implanted stem cells.

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