Abstract: Ischemic heart disease is the main cause of death and morbidity in most industrialized countries. Stem- and progenitor cell-based treatment approaches for ischemic heart disease are therefore an important frontier in cardiovascular and regenerative medicine. Experimental studies have shown that bone-marrow-derived stem cells and endothelial progenitor cells can improve cardiac function after myocardial infarction, clinical phase I and II studies were rapidly initiated to translate this concept into the clinical setting. However, as of now the effects of stem/progenitor cell administration on cardiac function in the clinical setting have not met expectations. Thus, a better understanding of causes of the current limitations of cell-based therapies is urgently required. Importantly, the number and function of endothelial progenitor cells is reduced in patients with cardiovascular risk factors and/or coronary artery disease. These observations may provide opportunities for an optimization of cell-based treatment approaches. This review provides a summary of current evidence for the role and potential of stem and progenitor cells in the pathophysiology and treatment of ischemic heart disease, including the properties, and repair and regenerative capacities of various stem and progenitor cell populations. In addition, we describe modes of stem/progenitor cell delivery, modulation of their homing as well as potential approaches to "prime" stem/progenitor cells for cardiovascular cell-based therapies.

DOI: https://doi.org/10.1387/ijdb.103219ct

Posted at the Zurich Open Repository and Archive, University of Zurich
ZORA URL: https://doi.org/10.5167/uzh-56283
Accepted Version

Originally published at:
DOI: https://doi.org/10.1387/ijdb.103219ct
Cell-based cardiovascular repair and regeneration in acute myocardial infarction and chronic ischemic cardiomyopathy – Current status and future developments

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Short running title: Cell therapy in ischemic heart disease
Key words: stem and progenitor cells, myocardial regeneration, myocardial infarction

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Words: 9286
Abstract

Ischemic heart disease is the main cause of death and morbidity in most of the industrialized countries. Stem- and progenitor cell-based treatment approaches for ischemic heart disease are therefore an important frontier in cardiovascular and regenerative medicine. Based on experimental studies demonstrating that bone-marrow-derived stem and endothelial progenitor cells can improve cardiac function after myocardial infarction, clinical phase I and II studies were rapidly initiated to translate this concept into the clinical setting. However, as of now the effects of stem/progenitor cell administration on cardiac function in the clinical setting did not meet the expectations. Thus, a better understanding of causes of the current limitations of cell-based therapies is urgently required. Importantly, the number and function of endothelial progenitor cells is reduced in patients with cardiovascular risk factors and/or coronary artery disease. These observations may provide opportunities for an optimization of cell-based treatment approaches.

This review provides a summary of the current evidence for the role and potential of stem and progenitor cells in the pathophysiology and treatment of ischemic heart disease, including the properties and repair and regenerative capacities of various stem and progenitor cell populations. In addition, we describe modes of stem/progenitor cell delivery, modulation of their homing as well as potential approaches to “prime” stem/progenitor cells for cardiovascular cell-based therapies.
Coronary artery disease, i.e. acute myocardial infarction and ischemic cardiomyopathy, are the main causes of death in most of the developed countries and are a major socioeconomic healthcare problem (Landmesser et al. 2005). Despite improved pharmacological therapy and coronary revascularization procedures by either percutaneous coronary intervention PCI or coronary artery bypass surgery CABG there is still a major need for novel therapeutic approaches (Landmesser et al. 2005; Ford et al. 2007). Whereas current treatment strategies aim largely to limit or delay progression of cardiac dysfunction (Landmesser et al. 2005; Landmesser et al. 2009; Segers et al. 2008) stimulation of vascular and cardiac repair mechanisms, such as those mediated by stem/progenitor cells, has become an important focus of cardiovascular research (Landmesser 2009). In fact, in patients with ischemic heart failure it is unlikely that the inhibition of novel neurohormones other than catecholamines, angiotensin and aldosterone will further improve cardiovascular outcome, underlining the need for novel therapeutic concepts to promote cardiac repair (Landmesser et al. 2009).

Experimental and first small- to intermediate scale clinical studies have suggested the feasibility and safety of cell-based therapies in patients with ischemic cardiomyopathy (Landmesser 2009; Schachinger et al. 2006; Segers et al. 2008). Heterogeneous cell populations have been thoroughly investigated as potential sources of cardiac progenitors in cell-based therapy for ischemic heart disease. To date, different autologous adult stem and progenitor cells, in particular several subtypes of bone marrow-derived cells, isolated adipose tissue-derived or cardiac-derived stem/progenitor cells are under preclinical and clinical evaluation. Additionally, embryonic stem cells and induced pluripotent stem cells provide regenerative capacity and improve cardiac function after ischemia in animal models (Nelson et al. 2009; van Laake et al. 2008). In an attempt to update the current field of cell-based therapy for ischemic heart disease, this review will discuss: (1) relevant stem and progenitor cell populations in myocardial regenerative medicine, (2) routes of cell delivery, (3) current
status of clinical trials, (4) mechanisms of adult stem and progenitor cell therapy, (5) limitations of current treatment strategies and (6) future developments of cell-based therapy.
Overview of cell types for cardiac repair

Over the past decade, early small and intermediate sized clinical trials have examined the effects of skeletal myoblasts (Menasche 2008; Menasche et al. 2003), circulating endothelial progenitor cells (Assmus et al. 2002; Hirsch et al. 2006), and bone marrow- derived mononuclear cell populations (Schachinger et al. 2006; Wollert et al. 2004) for treatment of ischemic heart disease. In addition, several progenitor and stem cell types have been studied in animal models to examine their potential use, including embryonic stem cells (ESCs) (Laflamme et al. 2007; van Laake et al. 2008), hematopoietic stem cells (HSCs) (Murry et al. 2004; Templin et al. 2008), mesenchymal stem cells (MSCs) (Mangi et al. 2003), endothelial progenitor cells (EPCs) (Aicher et al. 2003; Giannotti et al. 2010; Sorrentino et al. 2007), and, most recently, resident cardiac stem cells (CSCs) (Beltrami et al. 2003; Laugwitz et al. 2005; Oh et al. 2003). Each cell types comprise unique profiles regarding isolation and culture, cell surface marker expression, transcription factors, expressed proteins, and ability to differentiate into other cell types:

**Adult stem and progenitor cells**

*Bone-marrow-derived and circulating adult stem/progenitor cells:* Stem/progenitor cells isolated from the bone marrow, peripheral blood, and other tissues have been used in cell-based treatments for ischemic heart disease. In contrast to pluripotent embryonic stem cells, adult stem cells display a limited and still controversial transdifferentiation capacity towards cardiomyocytes. The two major subsets of bone marrow-derived stem cells are HSCs and MSCs. The true bone-marrow stem cells comprise <0.01% of the total bone marrow cells (Abkowitz et al. 2002; Pittenger et al. 2004) and may be isolated by direct marrow aspiration or obtained from peripheral blood after cytokine mobilization. Compared with other stem cell types, these cells appear to be present in greater numbers in vivo and have been studied particularly well, at least in part due to the fact that they can be rather easily obtained. Other
multipotent progenitor cells located in the bone marrow include side-population cells, which are characterised by their ability to efflux Hoechst dye (Challen et al. 2006).

Hematopoietic stem/progenitor cells express CD34 and CD133 cell surface antigens and have shown the ability to home to injured myocardium, but whether they differentiate into cardiomyocytes has been debated (Jackson et al. 2001; Murry et al. 2004).

Mesenchymal stem cells are present in adult tissues including the bone marrow and adipose tissue (Tomita et al. 1999). Criterions for their characterization have recently been summarized by a position statement of the international society for cellular therapy and include the expression of CD105, CD73 and CD90 and lack of expression of markers such as CD34, CD45, CD14 or CD11b, CD79alpha or CD19 and HLA-DR surface molecules and their ability to differentiate into osteoblasts, adipocytes, and chondroblasts in vitro (Conget et al. 1999) (Dominici et al. 2006). MSCs can be isolated and expanded easily and have been suggested to improve left ventricular function after myocardial infarction (Makino et al. 1999; Schuleri et al. 2008; Toma et al. 2002) (Mangi et al. 2003). Furthermore, non-invasive multimodality imaging has suggested that therapy after myocardial infarction with allogeneic MSCs promotes active cardiac repair in vivo (Amado et al. 2006).

It has been proposed by experimental in vitro data that adipose tissue–derived MSCs may transdifferentiate into cardiomyocyte-like cells and endothelial cells (Planat-Benard et al. 2004; Planat-Benard et al. 2004). However, as discussed above, there is no definite proof as of today for a complete transdifferentiation into cardiomyocytes. Adipose cells have been regarded as an attractive source because they are available in high quantities and easy to obtain.

Endothelial progenitor cells comprise a heterogenous circulating cell population likely derived largely from the bone marrow (Urbich et al. 2004). Different types of endothelial progenitor cells have been proposed, in particular “early” and “late” EPCs, based on their appearance in the culture of circulating mononuclear cells in endothelial medium (Hur et al. 2004). Early
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EPCs promote likely endothelial repair (Giannotti et al. 2010) and angiogenesis (Sievking et al. 2008) largely by paracrine effects, whereas late EPCs, that are very low in number, may become endothelial cells. The differentiation potential of early EPCs into cardiomyocytes has been questioned (Gruh et al. 2006).

Endothelial progenitor cells isolated from patients with diabetes or hypertension display a reduced activity in promoting re-endothelialization of denuded arteries and blood flow recovery after ischemia when transplanted into nude mice (Giannotti et al. 2010; Landmesser et al. 2004; Sorrentino et al. 2007), pointing to an important limitation of current cell-based treatment approaches in these patients. The functional deficits that cause these reduced in vivo activities remain to be further characterized, but likely include reduced nitric oxide availability and an accelerated senescence (Giannotti et al. 2010; Sorrentino et al. 2007). Notably, assays of a reduced functionality of bone-marrow-derived mononuclear cells, such as impaired migration or diminished colony formation capacity in vitro, have been associated with a decreased functional benefit in cell therapy trials (Assmus et al. 2007).

**Fetal and Umbilical Cord Blood cells** may possess greater plasticity than adult progenitor cells because of their prenatal origin. Umbilical cord blood contains a number of progenitor cell populations, including HSCs, MSCs, and unrestricted somatic stem cells, however, evidence of pluripotency after in vitro expansion is still lacking. Animal studies have been result in an improvement in left ventricular function (Iwasaki et al. 2009; Kim et al. 2005).

**Resident cardiac stem and progenitor cells** are a relatively rare cell population in the heart, which have been classified according to surface marker or transcription factor expression (Beltrami et al. 2003; Hierlihy et al. 2002; Oh et al. 2003). C-Kit+ cells have the capacity for self-renewal, clonogenicity, and pluripotency through differentiation into myogenic, endothelial, and smooth muscle lineages in vitro and may contribute to repair of ischemic myocardium (Beltrami et al. 2003). A second population of cardiac stem cells that express stem cell antigen-1 (Sca-1) have been differentiated into cells expressing cardiac specific
markers in vitro (Oh et al. 2003). Furthermore, it has been demonstrated that Isl1+ cells display mature cardiac phenotype including expression of myocytic markers in the absence of cell fusion, intact calcium cycling, and generation of action potentials in co-culture experiments with neonatal cardiomyocytes (Laugwitz et al. 2005). Cardiospheres, which are spherical clusters of cells that can be obtained with a cardiac biopsy, are plated and grown in culture to yield cardiosphere-derived cells in addition to other populations of resident cardiac progenitors (Smith et al. 2008). A recent proof-of-concept study demonstrated that cardiospheres could be isolated, and expanded to provide a potentially useful population of autologous cardiac stem cells (Messina et al. 2004). Several experimental studies using different preparations of cardiac-derived stem/progenitor cells have demonstrated positive effects on left ventricular function, remodeling, and infarct size; however, this has not been observed in all studies (Beltrami et al. 2003; Li et al. 2009; Oh et al. 2003). In particular, no long-term engraftment and benefit has been observed after transplantation of Sca-1-positive cardiac derived stem/progenitor cells.

*Skeletal myoblasts* transplantation into the heart as a cell-based strategy improved left ventricular function and reduced cardiac remodelling either to mechanical or scaffolding effects (Menasche 2008; Menasche et al. 2003). Unfortunately, skeletal myoblasts do not transdifferentiate into cardiomyocytes (Menasche 2008). Remarkably, these cells lack electrical integrity and can therefore induce arrhythmias (Menasche et al. 2008). Moreover these cells fail to show long term beneficial effects on LV-function (Menasche et al. 2008). A small randomized controlled trial found that application through a 3-dimensional guided catheter system was favourable in terms of left ventricular function, quality of life and symptoms relief (Dib et al. 2009). However, the first randomized placebo-controlled study of myoblast transplantation (MAGIC trial) failed to improve cardiac function as assessed by echocardiography (Menasche et al. 2008).
Embryonic stem cells are undifferentiated, pluripotent cells obtained from the inner cell mass of blastocysts that have the most promising potential for organ regeneration (Segers et al. 2008; Smith 2001). Their unlimited capacity for differentiation has garnered incremental interest for their use in regenerative cardiology. Previous studies of ischemia and reperfusion showed improved cardiac function, directly related to paracrine effects, after transplantation of undifferentiated murine ESCs (Crisostomo et al. 2008; Min et al. 2003). Of note, transplantation of undifferentiated murine ESCs can result in teratoma formation (Nussbaum et al. 2007). The risk can be reduced by transplanting pre-differentiated ESC-derived cardiomyocytes. In post-infarcted rat hearts, such cells ameliorate cardiac function and blunt left ventricular remodeling without teratoma formation (Caspi et al. 2007; Laflamme et al. 2007). Nevertheless, further investigations of tumor formation, immunologic responses and regenerative capacity are required to delineate the therapeutic potential of differentiated ESC. Furthermore, the techniques by which ESCs are obtained have raised considerable social and ethical concerns, hampering the discovery process for this phenotype both in the preclinical and clinical arena (Murry et al. 2008; Passier et al. 2008).

Induced Pluripotent Stem Cells (IPSCs) can be generated by retroviral transduction of so-called ‘stemness’ transcription factors (Geoghegan et al. 2008; Takahashi et al. 2007; Yu et al. 2007). Such cells can be maintained in culture for several months and induced to differentiate into lineages of all three germ layers, including cardiomyocytes, with electrophysiological properties and a gene expression profile that is similar to ESC-derived cardiomyocytes (Mauritz et al. 2008; Nelson et al. 2009). To reduce the risk of insertional mutagenesis following infection with retroviral vectors, the technique has recently been refined to incorporate virus-free approaches for gene delivery (Okita et al. 2008). Furthermore, a recent study was able to generate human-induced pluripotent stem cells by direct delivery of reprogramming proteins without DNA vectors (Kim et al. 2009). Also, the generation of functional cardiomyocytes from human induced pluripotent stem cells has been reported (Zhang et al. 2009). The strategy of reprogramming somatic cells could be also
used to develop patient-specific stem cells, which could be a unique resource in studying genetic mechanisms of disease development, drug actions, and regenerative biology.
Routes of cell delivery

To date several routes of cell delivery are employed, including (1) intravenous (Barbash et al. 2003); (2) intracoronary (Strauer et al. 2002), (3) direct transepicardial (intramyocardial) (Perin et al. 2006) or catheter-based transendocardial (intramyocardial) injection using electromechanical voltage mapping (Sherman et al. 2006), and (4) a recently implemented approach of transvenous injection into coronary veins (Thompson et al. 2003). Each delivery method has its own risks and benefits, and their suitability may also depend on the cell type used.

(1) The least invasive technique is systemic intravenous infusion, which involves injecting progenitor cell suspensions into a vein followed by homing of the cells to the injured myocardium (Price et al. 2006). The primary disadvantage of this approach is that cells may be trapped in the pulmonary circulation before they reach the systemic circulation (Barbash et al. 2003; Templin et al. 2006).

(2) The most frequently used route of application in clinical studies is percutaneous coronary cell delivery. Under these conditions, cells are injected via an over-the-wire balloon catheter into the vessel supplying the ischemic territory. The balloon is intermittently inflated to transiently stop coronary flow and allow cell distribution. Interestingly, a recent study in the porcine myocardial infarction model has suggested that prolonged balloon inflation is not necessary for the intracoronary approach using mononuclear bone-marrow-derived cells (Tossios et al. 2008). Notably, for intracoronary injection of mesenchymal stem cells in a dog model, however, induction of microinfarctions has been described (Vulliet et al. 2004). In some studies it was observed that the percutaneous intracoronary approach showed an increased engraftment of transplanted MSCs in pigs after myocardial infarction as compared to intramyocardial injection or intravenously transplanted cells (Freyman et al. 2006) (Moscoso et al. 2009). However, a recent study using bone marrow-derived mononuclear cells showed a 7-fold greater number of cells in the myocardium for the intramyocardial method and a 10-fold greater number of cells in the lungs in the intracoronary group of pigs.
(Makela et al. 2009). The opposing results may be related to different cell populations. In any case, the intracoronary approach requires transmigration of the endothelial barrier, whereas after intramyocardial injection the cells are largely primarily in the interstitial space.

(3) Direct intramyocardial injections can be applied through the epicardium into the underlying ischemic myocardium during cardiac surgery when the heart is fully exposed. An advantage of this approach is the ability to target specific areas of myocardium and scar under direct visualization. In contrast, the benefit of direct intramyocardial injection may be limited by poor cell diffusion (Melo et al. 2004) and applications for larger areas require multiple injections.

Percutaneous transendocardial delivery is performed through direct injection of cells into the myocardium using percutaneous catheters with small injection needles. Electromechanical mapping is an excellent technique supporting the percutaneous transendocardial approach to identify ischemic territories (Smits et al. 2003). Percutaneous coronary infusion and percutaneous transendocardial delivery are most likely more appropriate in patients without a planned surgical intervention. In an experimental study, intramyocardial but not intracoronary injection of bone-marrow cells after myocardial infarction was associated with an increased risk of ventricular tachycardias (Fukushima et al. 2007). The authors observed that the intramyocardial distribution of bone-marrow cells was more homogeneous after i.c. as compared to i.m. injection, and was associated with less inflammatory response (Fukushima et al. 2007).

Therefore, the most appropriate route of cell application likely depends on the clinical setting (preferably i.c. in the acute myocardial infarction) and the cell type used.
Clinical trials

Therapeutic use of bone marrow derived cells (BMCs) in the setting of acute myocardial infarction has been studied in more than 1000 patients worldwide. These BMCs include hematopoietic and endothelial progenitor cells (approximately 2–4%), mesenchymal stem cells (MSC; ~0.1%) and a very small number of side population cells. To date four meta-analyses have been published (Abdel-Latif et al. 2007; Hristov et al. 2006; Lipinski et al. 2007; Martin-Rendon et al. 2008) suggesting the feasibility and safety of BMC application with a potential modest beneficial effects on left ventricular ejection fraction (LVEF) (an increase of approximately 3%). A reduction in ventricular volumes; a reduction in infarct or lesion size, ranging from 3.5% to 5.6%; and improved regional LV function (Lipinski et al. 2007). Although these effects on LV function are less than what was expected based on experimental studies in rodents, it should be noted that several of the established clinical therapies which do have an impact on prognosis in patients with ischemic cardiomyopathy, such as ACE inhibitor or beta-blocker therapy, are associated with a similarly small change in LV ejection fraction (Reffelmann et al. 2009). Furthermore, a patient with the greatest amount of myocardial damage displayed the greatest benefit (Janssens et al. 2006). In addition one study indicates that transplantation of bone marrow cells may have an impact on coronary flow reserve (Erbs et al. 2007). Finally, the number of injected cells may play a key role for the effects on LVEF (Martin-Rendon et al. 2008). Interestingly, the meta-analyses suggested a trend toward a reduction in recurrent MI (Martin-Rendon et al. 2008) and in the REPAIR-AMI (Intracoronary Progenitor Cells in Acute Myocardial Infarction) trial of 204 patients, even reported a significant reduction in mortality, rehospitalisation for heart failure, and repeated revascularization (Assmus et al. 2010; Schachinger et al. 2006). Of note, the overall benefit demonstrated in the meta-analyses with regard to left ventricular function needs to be tempered by the results of 3 other trials (Lunde et al. 2008; Meyer et al. 2006; Tendera et al. 2009), which demonstrated either no benefit or an initial benefit that was not sustained beyond 6 months. In this regard, it has been suggested, that differences in cell
isolation protocols may have an impact on the functional capacity of the cells in the REPAIR-AMI1 and ASTAMI (Autologous Stem Cell Transplantation in Acute Myocardial Infarction) trials and therefore may account for the discordant results. Patients with reduced LV function may in fact have more benefit from BMC therapy as suggested by retrospective analyses of several of the above trials (Meyer et al. 2009) (Schachinger et al. 2006).

Additionally, there are also studies using enriched CD34+ or CD133+ hematopoietic and endothelial progenitor cells from bone marrow or after mobilization with the cytokine G-CSF (Losordo et al. 2007). Other studies used circulating blood-derived cells that have been isolated from mononuclear blood cells and selected ex vivo by culturing in endothelium-specific medium for 3 days.

The two APOLOLO trials aim to evaluate whether adipose tissue-derived cells enhances heart function in acute or chronic ischemia (APOLLO trials).

Further clinical trials are underway investigating the use of c-kit+ cardiac stem cells in patients with chronic ischemic heart disease.

Table 1 provides an overview of current ongoing cell therapy trials in patients with myocardial infarction / ischemic cardiomyopathy.
Potential mechanisms mediating effects of adult stem/progenitor cell-based therapy on cardiac function

There are many open questions at present with respect to the understanding of mechanisms of circulating or bone marrow-derived stem/progenitor cell-mediated cardiac repair (Burt et al. 2008; Landmesser 2009; Segers et al. 2008). Whereas initially, a rapid transdifferentiation of bone-marrow derived stem cells into cardiomyocytes was postulated to explain the effects on cardiac function (Orlic et al. 2001) several later studies have indicated that other mechanisms, in particular promotion of cardiac vascular growth, may mediate the observed beneficial effects on left ventricular (LV) function, likely at least in part due to paracrine effects of endothelial progenitor or bone-marrow-derived stem cells (Gnecchi et al. 2008; Murry et al. 2004). This concept was further supported by the observation that circulating endothelial progenitor cells and bone marrow-derived stem/progenitor cells may increase myocardial neovascularisation and perfusion in patients (Erbs et al. 2007). Furthermore, animal studies have suggested that bone marrow-derived progenitor cells (Templin et al. 2008; Templin et al. 2006) and human endothelial progenitor cells (Kocher et al. 2001) improve cardiac function in rodents with myocardial infarction by promotion of neovascularisation and prevention of apoptosis. It is well known from earlier studies, that myocardial capillary growth plays a critical role for maintenance of cardiac function (Giordano et al. 2001). In addition to enhanced neovascularization, paracrine factors released by the incorporated cells may beneficially influence cardiac repair by protecting cardiovascular cells from apoptotic stimuli or even by activating cardiac-resident stem cells to enhance the endogenous repair capacity (Uemura et al. 2006; Urbich et al. 2005). Paracrine mechanisms may additionally prevent inflammation, fibrosis and reactive hypertrophy (Burchfield et al. 2008). Moreover, the injection of conditioned medium in which MSCs were cultured results in the improvements of left ventricular function and reduced apoptosis (Gnecchi et al. 2005). In a further article, SFRP2 (secreted frizzled-related protein II), which modulates the Wnt (winglesstype MMTV integration site family) signaling system and the expression of
antiapoptotic genes, was shown to be the key factor released by AKT-1 (v-akt murine thymoma viral oncogene homolog 1)–enriched MSCs (Mirotsou et al. 2007). Recently, we analyzed the secreted proteome of a hematopoietic progenitor cell line which exert modulating effects on tissue repair and regeneration. In this study a subset of 95 different proteins were identified in a mass spectrometry based approach whereas the cytokines IL-6 and IL-13 and the chemokines MCP-1, MCP-3, MIP1-a, and MIP1-b were identified using an immunological approach (Luecke et al. 2010). Furthermore, experimental data have shown that interleukin 10 from transplanted bone marrow mononuclear cells may contribute substantially to cardiac protection after MI (Burchfield et al. 2008). Additionally, other cytokines and growth factors from transplanted progenitor cells may exert important paracrine effects like vascular endothelial growth factor, stromal cell–derived factor, angiopoietin 1, hepatocyte growth factor, insulinlike growth factor 1, and periostin, among others (Kinnaird et al. 2004; Uemura et al. 2006; Urbich et al. 2005). Although the direct effects of cell therapy are not entirely understood, the majority of studies suggest that stem/progenitor cells may have a beneficial effect on cardiac function.
Limitations of current cell-based treatment approaches

There is currently a limited knowledge on the role of the required number and function of bone marrow cells needed for an optimal effect on cardiac repair. Low cell dosages might in fact limit the efficacy of bone marrow cell therapy. For example, in the ASTAMI trial, the median number of mononuclear cells injected was $68 \times 10^6$, and the median number of CD34$^+$ cells was $0.7 \times 10^6$. There were no significant differences between the BMC and control group in changes in LVEF, end-diastolic volume, or infarct size (Lunde et al. 2006).

In the BOOST trial, the average number of mononuclear BM cells was $24.6 \times 10^8$, and the number of CD34$^+$ cells was $9.5 \times 10^6$. Six months after randomisation, global LVEF increased from 50.0% to 56.7% ($P=0.0026$), albeit this difference was not maintained at long-term follow-up (Wollert et al. 2004). In the TOPCARE-AMI trial, the average number of mononuclear BM cells was $24.5 \times 10^7$, and the number of CD34$^+$ cells was $7 \times 10^6$. In patients receiving progenitor cells, global LVEF increased from 51.6% to 60.1% ($P=0.003$) (Schachinger et al. 2006). To treat a patient of 80 kg with a high dose cell strategy as described in some animal studies ($1 \times 10^7$ cells/25g) would require $32 \times 10^9$ CD34$^+$ cells (adjusted to body weight), which exceeds the number of HPCs used in clinical trials by a factor of ~3000 (Assmus et al. 2002). Therefore, strategies allowing rapid ex vivo progenitor cell expansion may improve cell-based clinical treatment regimens.

Another potential reason for discrepancies between experimental and clinical studies with respect to the impact of circulating or bone marrow-derived stem/progenitor cell therapy on cardiac function is related to the fact, that the effect of stem/progenitor cells obtained from young healthy rodents in experimental studies is compared with effects of stem/progenitor cells obtained from older patients with chronic coronary disease in clinical studies. In support of this concept, a substantially impaired in vivo vascular repair capacity of stem/progenitor cells derived from patients with cardiovascular risk factors as compared to healthy subjects has been observed (Giannotti et al. 2010; Sorrentino et al. 2007), and very recently a
severely reduced vascular and cardiac repair capacity of stem/progenitor cells derived from patients with ischemic cardiomyopathy. Additionally, cell therapy is currently limited by low rates of cell engraftment after intracoronary delivery and poor cell survival after intramyocardial injections (Hofmann et al. 2005; Menasche 2008; Schachinger et al. 2008). Furthermore, the amount of circulating progenitor cells in patients with cardiac ischemic disease comorbidities such as diabetes mellitus, hypertension and hypercholesterolemia is reduced (Imanishi et al. 2005; Vasa et al. 2001). This is problematic as this cohort is essentially the very one that would need to be treated with progenitor cells. These challenges require further research to enhance the therapeutic efficiency of stem and progenitor cells in the treatment of ischemic heart disease. This includes the use of more potent cells with a higher cardiac regeneration capacity (for instance induced pluripotent stem cells) and strategies for improving cell homing, survival, engraftment and repair capacity, of transplanted cells.
Future directions of cell based-therapy for ischemic heart disease

The development of cell-based therapies for ischemic heart disease faces several practical challenges which need to be addressed. Several studies have indicated a reduced cardiac and vascular repair capacity of patient-derived adult stem/progenitor cells as compared to cells obtained from healthy subjects (Giannotti et al. 2010; Sorrentino et al. 2007). Therefore, the mechanisms leading to stem/progenitor cell dysfunction need to be better characterized and will provide interesting novel approaches to optimize cell-based treatment approaches. Moreover, strategies to improve cardiac homing and engraftment of stem/progenitor cells may optimize the effect the results of this treatment approach (Pons et al. 2008; Pons et al. 2009; Tang et al. 2009; Zhao et al. 2009).

One interesting strategy for the improvement of current cell-based approaches may be the combination of cell- and gene therapy. In this regard, we have demonstrated long-term self renewal and unlimited expansion of hematopoietic progenitor cells using human β-catenin gene transfer (Templin et al. 2008). Administration of defined β-catenin-HPCs after MI reduces infarct size and improves left ventricular function and dimensions in a threshold-dependent manner (Templin et al. 2008). This effect is associated with improved angiogenesis and reduced apoptosis in the infarct border zone. Furthermore, β-catenin-HPCs have greater therapeutic efficacy than control-transduced HPCs (GFP-HPCs), demonstrating a beneficial effect of β-catenin transduction on myocardial repair (Templin et al. 2008). Other recent studies have investigated specific protein expression through ex vivo modifications of receptors and molecules involved in progenitor cell paracrine signaling, homing, and survival. Numerous investigators have modified MSCs to overexpress protective growth factors such as VEGF (Yang et al. 2007), upregulate homing receptors (Cheng et al. 2008), upregulate cell survival signaling pathways involving Akt (Mangi et al. 2003) and overexpress ischemia-protective proteins including heme oxygenase-1 (Tang et al. 2005).

A recent interesting study combined a genetic and pharmacologic inhibition of dipeptidylpeptidase IV with G-CSF-mediated stem cell mobilization after myocardial infarction
in mice. This approach leads to increased myocardial homing of circulating CXCR-4+ stem cells, and improved heart function and survival (Zaruba et al. 2009). Pretreatment of endothelial progenitor cells with statins, eNOS-overexpression of PPAR-gamma agonists before transfer increases their migratory, invasive, and neovascularization capacity - effects that are mediated by activation of endothelial nitric oxide synthase (Shao et al. 2008; Spyridopoulos et al. 2004). Similarly, own results showed that prestimulation of endothelial progenitor cells from diabetic individuals with the peroxisome proliferator activated receptor γ-agonist rosiglitazone, enhances nitric oxide availability and the in vivo endothelial repair capacity of these cells (Sorrentino et al. 2007). MicroRNAs have been identified as unexpectedly potent regulators in cardiovascular biology, controlling vascular growth, endothelial NO synthase and stem cell differentiation and may be interesting targets to optimize cell-based therapies (Suarez et al. 2007; Suarez et al. 2009; van Rooij et al. 2008).
Conclusion

Development of cell-based strategies for cardiac repair for the use in clinical routine is an exciting and challenging task. The concept of cardiac regeneration or rejuvenation and protection via paracrine mechanisms responses to reduce cardiomyocyte apoptosis and increase angiogenesis needs to be further developed and optimized, and represents one important line of current research. One such approach represents the combination of cell and gene therapy, by either transduction of genes into stem cells or modifying stem cells as vectors for drug delivery. Moreover, novel cell types with a true cardiomyocyte transdifferentiation potential such as iPS provide another important line in the development of cell-based approaches for cardiac repair. Upscaling and safety of such an approach represent important challenges to be solved.
Funding

This work was supported by a grant of the Swiss National Research Foundation “Sonderprogramm Universitäre Medizin” [Nr. 33CM30-124112/1], Swiss National Research Foundation grant (310000-122339), and the Zurich Center for Integrative Human Physiology.
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Figures:

**Fig.1. Future developments of cell-based therapy for ischemic cardiomyopathy (modified after Templin et al. 2010).** Ex vivo modulation (e.g. microRNA modulation or combined gene and cell-therapy) of bone marrow derived progenitor cells may be used to improve current adult cell treatment strategies. Inducible pluripotent stem cells have the ability to differentiate into cardiovascular cells and exhibits great potential for cardiac regeneration.
### Table 1

#### ONGOING CELL THERAPY TRIALS IN PATIENTS WITH ACUTE MYOCARDIAL INFARCTION / ISCHEMIC CARDIOMYOPATHY

<table>
<thead>
<tr>
<th>ClinicalTrials.gov Identifier</th>
<th>Trial name</th>
<th>Number of patients</th>
<th>Cell type</th>
<th>Primary end point</th>
<th>Route of cell delivery</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCT00711542</td>
<td>REPAIR-ACS</td>
<td>100</td>
<td>Bone marrow-derived progenitor cells</td>
<td>Coronary flow reserve in the infarct vessel</td>
<td>Intracoronary</td>
</tr>
<tr>
<td>NCT03551186</td>
<td>SWISS-AMI</td>
<td>150</td>
<td>Bone marrow mononuclear cells</td>
<td>LVEF</td>
<td>Intracoronary</td>
</tr>
<tr>
<td>NCT00994178</td>
<td>TECAMI</td>
<td>120</td>
<td>Bone marrow mononuclear cells</td>
<td>LVEF; Left ventricular end-systolic volume</td>
<td>Intracoronary</td>
</tr>
<tr>
<td>NCT01335076</td>
<td>EMRISTID</td>
<td>200</td>
<td>Bone marrow mononuclear cells</td>
<td>LVEF</td>
<td>Intracoronary</td>
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<tr>
<td>NCT00684382</td>
<td>The TIMI Study</td>
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<td>Bone marrow mononuclear cells</td>
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<tr>
<td>NCT00684860</td>
<td>The Last TIMI Study</td>
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<td>Bone marrow mononuclear cells</td>
<td>LVEF</td>
<td>Intracoronary</td>
</tr>
<tr>
<td>NCT00831836</td>
<td>ReNurW</td>
<td>50</td>
<td>Bone marrow mononuclear cells</td>
<td>LVEF; Occurrence of arrhythmia, heart failure</td>
<td>Intracoronary or death</td>
</tr>
<tr>
<td>NCT00874354</td>
<td>REVI-TALIZE</td>
<td>99</td>
<td>Bone marrow mononuclear cells</td>
<td>Safety and feasibility; LVEF</td>
<td>Intracoronary</td>
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<tr>
<td>NCT01150697</td>
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<td>59</td>
<td>Bone marrow mononuclear cells</td>
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<td>Intracoronary</td>
</tr>
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<td>NCT00939042</td>
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<tr>
<td>NCT00764543</td>
<td>RESSEL-AMI</td>
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<td>Bone marrow-derived progenitor cells</td>
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<tr>
<td>NCT00437710</td>
<td>CARDIAC</td>
<td>59</td>
<td>Bone marrow-derived stem cells</td>
<td>Mortality; Mortality and Morbidity; Left ventricular function</td>
<td>Intracoronary</td>
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<tr>
<td>NCT00275977</td>
<td>-</td>
<td>19</td>
<td>Bone marrow-derived stem cells</td>
<td>LVEF</td>
<td>Intracoronary</td>
</tr>
<tr>
<td>NCT00429922</td>
<td>SELECT-AMI</td>
<td>39</td>
<td>CD133+ enriched bone marrow cells</td>
<td>Safety; Myocardial thickening in non-viable segments / hypokinetic LV wall segments</td>
<td>Intracoronary</td>
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<tr>
<td>NCT00725707</td>
<td>TRACa Study</td>
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<td>Intracoronary</td>
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<tr>
<td>NCT00936119</td>
<td>ENACT-AMI</td>
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<td>Intracoronary</td>
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<td>NCT00501917</td>
<td>MAGIC Cell-M-Cembryokine Trial</td>
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<td>Intracoronary</td>
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<tr>
<td>NCT00555826</td>
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<td>Mesenchymal precursor cells</td>
<td>Fertility and safety</td>
<td>Transendocardial</td>
</tr>
<tr>
<td>NCT00877260</td>
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<td>220</td>
<td>Ex vivo cultured adult human mesenchymal stem cells</td>
<td>Left ventricular end systolic volume</td>
<td>Intravenous</td>
</tr>
<tr>
<td>CardiTherapies</td>
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<tr>
<td>NCT00893080</td>
<td>CADUCEUS</td>
<td>39</td>
<td>Cardiosphere-derived stem cells</td>
<td>Safety</td>
<td>Intracoronary</td>
</tr>
</tbody>
</table>

#### Ischemic cardiomyopathy

<table>
<thead>
<tr>
<th>ClinicalTrials.gov Identifier</th>
<th>Trial name</th>
<th>Number of patients</th>
<th>Cell type</th>
<th>Primary end point</th>
<th>Route of cell delivery</th>
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<td>Bone marrow progenitor cells</td>
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<td>NCT00824095</td>
<td>FOCUS</td>
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<td>Bone marrow mononuclear cells</td>
<td>Maximal oxygen consumption, left ventricular end systolic volume, reversible defect size</td>
<td>Transendocardial</td>
</tr>
<tr>
<td>NCT00852202</td>
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<td>Bone marrow-derived cardiopoietic cells</td>
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<td>Transendocardial</td>
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<td>NCT00656920</td>
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<td>Bone marrow-derived stem cells</td>
<td>Left ventricular volumes and contractility</td>
<td>Transendocardial during CABG</td>
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<tr>
<td>NCT00818418</td>
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<td>LVEF</td>
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<tr>
<td>NCT01049897</td>
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<td>CD133+ endothelial precursor cells</td>
<td>Regional and global myocardial contractility</td>
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<tr>
<td>NCT01936617</td>
<td>IMPACT-CABG</td>
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<td>Freedom from major adverse cardiac events</td>
<td>Transendocardial during CABG</td>
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<td>PERFECT</td>
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<td>CD133+ bone marrow stem cells</td>
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<td>Transendocardial during CABG</td>
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<td>NCT00452774</td>
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<td>Transendocardial during CABG</td>
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<td>CD34+ cells</td>
<td>Safety; LVEF, heart failure symptoms</td>
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<td>NCT00242242</td>
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<td>NCT01067618</td>
<td>MESSAMI</td>
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<td>Mesenchymal stem cells</td>
<td>Safety and feasibility</td>
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<td>The POST-ECCON-Pilot Study</td>
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<tr>
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<td>Mesenchymal cells / Bone marrow cells</td>
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<td>Transendocardial</td>
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<td>NCT00587980</td>
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<td>NCT00906862</td>
<td>PERCUTANEO</td>
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<td>Skeletal myoblasts</td>
<td>LVEF; Wall motion score index</td>
<td>Percutaneous</td>
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<td>NCT00826253</td>
<td>MARVEL</td>
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<td>Skeletal myoblasts</td>
<td>6-minute walk test; Quality of Life Questionnaire</td>
<td>Transendocardial</td>
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<td>NCT00474461</td>
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<td>Cardiac stem cells</td>
<td>Safety/efficacy Study</td>
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<tr>
<td>NCT00851086</td>
<td>ALCADIA</td>
<td>6</td>
<td>Cardiac-derived stem cells</td>
<td>Safety</td>
<td>Transendocardial during CABG</td>
</tr>
</tbody>
</table>

**Searching criteria for [http://www.clinicaltrials.gov](http://www.clinicaltrials.gov) (04/19/2010):** Cell therapy for myocardial infarction. - Cell therapy for ischemic cardiomyopathy

**Abbreviations:** CABG: coronary artery bypass grafting; LVEF: left ventricular ejection fraction; MACE: major adverse cardiac events; TE-SAE: defined as composite of death, non-fatal MI, stroke, hospitalization for worsening heart failure, cardiac perforation, pericardial tamponade, ventricular arrhythmias, Vf 5 sec, or with hemodynamic compromise or ar一套t fibrillation.