Developmental and Regenerative Biology of Multipotent Cardiovascular Progenitor Cells

Anthony C. Sturzu, Sean M. Wu

Abstract: Our limited ability to improve the survival of patients with heart failure is attributable, in part, to the inability of the mammalian heart to meaningfully regenerate itself. The recent identification of distinct families of multipotent cardiovascular progenitor cells from endogenous, as well as exogenous, sources, such as embryonic and induced pluripotent stem cells, has raised much hope that therapeutic manipulation of these cells may lead to regression of many forms of cardiovascular disease. Although the exact source and cell type remains to be clarified, our greater understanding of the scientific underpinning behind developmental cardiovascular progenitor cell biology has helped to clarify the origin and properties of diverse cells with putative cardiogenic potential. In this review, we highlight recent advances in the understanding of cardiovascular progenitor cell biology from embryogenesis to adulthood and their implications for therapeutic cardiac regeneration. We believe that a detailed understanding of cardiogenesis will inform future applications of cardiovascular progenitor cells in heart failure therapy and regenerative medicine. (Circ Res. 2011;108:353-364.)

Key Words: cardiovascular disease ■ stem cells ■ regeneration ■ cardiac development ■ cardiomyocytes

“Education consists mainly of what we have unlearned.”
—Mark Twain (1835–1910)

The view of the mammalian heart as a postmitotic organ, incapable of generating new heart muscle, has dominated cardiovascular science and medicine for over a century. To those who care for patients with cardiovascular diseases, their observations would give no reason to challenge this view. For instance, following the proximal occlusion of a major coronary artery, a billion or more cardiomyocytes are typically lost and replaced by noncontractile scar tissue.1 The injured heart attempts, ineffectively, to compensate for the loss of functioning myocardium, resulting in a downward spiral of adverse cardiac remodeling, neurohormonal activation, and, ultimately, congestive heart failure.2 However, as Mark Twain aptly alluded to, sometimes even our most basic assertions are found to be imprecise, askew, or just plainly wrong. Several practices in the recent history of cardiovascular medicine serve as prime examples: avoidance of β-blockers in heart failure, use...
of antiarrhythmics for suppression of ventricular ectopy following myocardial infarction, and estrogen replacement therapy for cardiovascular disease prevention are among the doctrines that have been “unlearned” in recent years.

Likewise, rapid advances in stem cell and regenerative biology have prompted the scientific community to reconsider the assumption that the infarcted myocardium is incapable of self-repair. In this regard, the concept that new myocytes might be generated in the diseased myocardium by administering exogenous stem cells elicited such overwhelming excitement by the medical community that treatment of cardiac patients with autologous stem cells were expedited into clinical trials. Although the exact benefit of such treatment remains to be defined, it is clear that an effective, safe, and durable therapy for cardiomyocyte replacement will require a detailed understanding of the fundamental biology of cardiac progenitor cells. In this review, we examine the existing knowledge of adult mammalian heart regeneration, provide an overview of cardiovascular progenitor cell biology, and highlight important questions that remain unanswered. A comprehensive understanding of developmental cardiovascular progenitor cells will help to inform our future regenerative strategies regardless of the source or type of cell used.

**Mammalian Cardiac Regeneration**

The animal kingdom is abundant with examples of spontaneous organ regeneration following injury. With respect to cardiac regeneration, the zebrafish has captured the most attention from the scientific community because of its remarkable capacity to replace substantial portions of its heart following ventricular amputation. By contrast, the remarkable capacity to replace substantial portions of its heart during postnatal development and into adult life, cardiomyocyte proliferation slows dramatically after birth.

Following injury, cardiomyocytes bordering the infarct zone rarely divide, although transgenic manipulation of specific genes and a small number of extrinsic factors have been shown to increase cardiomyocyte division in mice. For this and other reasons, the notion that mammalian cardiac tissue may harbor regenerative potential has been vigorously debated.

To explore this question in humans, Beltrami et al examined myocardial cells from the hearts of 13 patients who died shortly after a myocardial infarction. They found colocalization of metaphase chromosomes or Ki-67 labeling (a nuclear protein associated with cell proliferation) in cells that stained positively with cardiac sarcomeric protein and concluded that cardiomyocyte division had occurred in a human postinjured heart. In their samples, Ki-67 was expressed in 4% of myocytes in the zone that bordered the infarct, and in 1% of myocytes in regions distant from the scar. Compared to an age-matched control group, Ki-67 expression in infarcted hearts was 84 and 28 times higher in these regions, respectively, suggesting that significant myocyte proliferation may occur during normal aging and becomes further amplified in the context of a myocardial infarction. Based on these findings, the authors estimated that the entire population of human myocytes may turnover every 4.5 years.

The results from Beltrami et al, however, need to be examined in the context of normal postnatal cardiomyocyte maturation. Unlike many other differentiated cell types, cardiomyocytes often undergo a final round of nuclear division without cytokinesis during the first decade of life, resulting in approximately 25% of human cardiomyocytes becoming binucleated. Cardiomyocytes also retain the ability to undergo DNA synthesis without nuclear division (ie, endoreduplication). As a result, many cardiomyocyte nuclei are polyploid, containing twice or even higher multiples of the normal content of DNA. These confounding issues regarding cardiomyocyte DNA synthesis and nuclear mitosis raise concern that the findings observed by Beltrami et al may reflect, in part, the occurrence of endoreduplication or acytokinesis in the injured heart.

These issues were addressed recently by Bergmann et al using a novel method of radiocarbon dating of DNA. As a result of aboveground nuclear testing during the Cold War, atmospheric levels of carbon-14 (14C) rose dramatically, ultimately becoming incorporated into the food chain and eventually into the DNA of all plant and animal cells. Following the signing of the Limited Nuclear Test Ban Treaty in 1963, levels of atmospheric 14C dropped precipitously, but residual 14C from the initial testing still persisted in the DNA of cells “born” during that era. By exploiting this unusual period in human history, these investigators have effectively determined the lifespan of a variety of cell types within the human body, and in the process, provide the most definitive evidence to date that human cardiomyocytes are renewed during postnatal life.

Applying the 14C approach to examine human heart specimens, Bergmann et al showed that the chronological age of their subjects was slightly older than the mean age of their cardiomyocyte DNA. In patients born before the Cold War,

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**Non-standard Abbreviations and Acronyms**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tr>
<td>Bry</td>
<td>brachyury T</td>
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<tr>
<td>c-Kit</td>
<td>stem cell factor receptor</td>
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<tr>
<td>eGFP</td>
<td>enhanced green fluorescent protein</td>
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<tr>
<td>ES</td>
<td>embryonic stem (cell)</td>
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<tr>
<td>Flk1</td>
<td>fetal liver kinase 1</td>
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<tr>
<td>GATA4</td>
<td>GATA binding factor 4</td>
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<tr>
<td>iPS</td>
<td>induced pluripotent stem (cell)</td>
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<tr>
<td>Islet1</td>
<td>Islet-1 transcription factor, LIM/homeodomain</td>
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<tr>
<td>Mdr1</td>
<td>multidrug resistance 1</td>
</tr>
<tr>
<td>Mef2</td>
<td>myocyte enhancer factor 2</td>
</tr>
<tr>
<td>Mesp1</td>
<td>mesoderm posterior 1</td>
</tr>
<tr>
<td>Nkx2.5</td>
<td>NK2 transcription factor related, locus 5</td>
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<tr>
<td>Sca-1</td>
<td>stem cell antigen 1</td>
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<td>SP</td>
<td>side population</td>
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<tr>
<td>Tbx</td>
<td>T-box transcription factor</td>
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<td>WT1</td>
<td>Wilms’ tumor protein</td>
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the concentration of 14C in their cardiomyocyte DNA exceeded the atmospheric concentration of 14C at the time of their birth, whereas patients born during or after the nuclear testing had a lower concentration of 14C, firmly establishing that human cardiomyocytes synthesize new DNA after birth. By meticulously sorting cardiomyocyte nuclei and excluding cells with more than a single set of chromosomes, the investigators were able to account for the effects of cardiomyocyte binucleation and polyploidy. Taking these factors into consideration, they concluded that cardiomyocyte renewal does occur in humans, albeit much more slowly than what was suggested by Beltrami et al. Mathematical modeling suggested that cardiomyocyte renewal is an age-dependent process, with rates of ≈1% turnover per year at age 20, declining to ≈0.4% of total cardiomyocytes per year by the age of 75. Over an average human lifespan, this translates to about half of an individual’s cardiomyocytes being replaced.

If cardiomyocyte renewal does occur in mammals, whether these cells originate from a stem/progenitor cell pool or are derived from already differentiated cardiomyocytes remains an open question. To investigate whether resident cardiac stem cells or precursor cells can participate in regeneration, Hsieh et al studied cardiomyocyte turnover in mice using a tamoxifen-driven Cre-lox system that induced expression of an enhanced green fluorescent protein (eGFP) in differentiated cardiomyocytes only. An early “pulse” of tamoxifen induced labeling of cardiomyocytes, detectable by eGFP fluorescence. This was followed by a “chase” period (eg, aging over 1 year, myocardial infarction, and pressure overload) during which unlabeled progenitor cells could differentiate into cardiomyocytes. If new cardiomyocytes are formed from progenitors, there should be a decrease in the percentage of eGFP-expressing cardiomyocytes over time as new unlabeled cardiomyocytes replace them. When the mice were analyzed 1 year after tamoxifen treatment, but without injury, the investigators found no detectable replacement of cardiomyocytes by progenitor cells during normal aging. The authors then looked for repair by stem/progenitor cells after cardiac stress, which was induced either through myocardial infarction or through pressure overload by aortic banding. After either form of cardiac stress, the percentage of eGFP+ cardiomyocytes decreased, suggesting that damaged cells were replaced with new cardiomyocytes that had differentiated from uncombined progenitors. It was estimated that 15% of the cardiomyocytes in the perinfarct areas and 5% of the cardiomyocytes in infarct-remote areas were derived from uncombined progenitors. In hearts that were challenged with pressure overloading, 5% of cardiomyocytes were found to arise from unlabeled progenitors. These results suggest that progenitor cells are recruited to become cardiomyocytes after injury, but not during normal aging. In addition, the authors were able to detect small numbers of cells in the infarcted hearts staining positive for stem cell markers such as c-Kit and Nkx2.5 (NK2 transcription factor related, locus 5), further adding plausibility to the notion that the new cardiomyocytes may have been formed from a cardiac stem/progenitor cell pool. Although the regenerative potential of the mammalian heart appears to be quite limited, and clearly is not sufficient to cope with the widespread loss of cardiomyocytes seen in a myocardial infarction, these studies point toward an unexpected source of cells in the adult heart with cardiogenic potential.

Cardiac Progenitors in the Rodent Adult Heart

The persistence of cardiac progenitors in the adult heart would provide an avenue to direct regeneration of cardiomyocytes that are lost because of cardiac injury and an opportunity to bypass the need for cell transplantation, one of the major challenges in regenerative medicine. These potential advantages led investigators to search for novel heart muscle–forming cells resident in the postnatal and adult myocardium (Table). To identify a progenitor cell population in the adult heart, a number of investigators have used a combination of cell surface markers traditionally used to identify stem cell populations in other tissues. Beltrami et al reported isolating clonogenic, self-renewing cells that are capable of differentiating into cardiomyocytes, vascular smooth muscle cells, and endothelial cells. These cells are negative for many blood lineage markers (Lin-), and positive for c-Kit, the receptor for stem cell factor. In the adult rat myocardium, c-Kit+ cells are rare (1 per 10 000 myocytes), and heterogeneous, with a minority (7% to 10%) expressing early cardiac transcription factors such as GATA4 (GATA binding factor 4), Mef2 (myocyte enhancer factor 2), and Nkx2.5. In vitro, c-Kit+ clones differentiate into cells that biochemically resemble mature cardiomyocytes, although functionally, organized sarcomeres and spontaneous contractile activity are not observed.

Although results from transplantation studies using adult c-Kit+ cells in animal models have been mixed, Beltrami et al observed a band of regenerating myocardium and a contribution of labeled cells to blood vessels when c-Kit+ cells were injected into the infarct border zone of hearts from syngeneic rats after myocardial infarction. The tagged cells expressing sarcomeric proteins were small relative to cardiomyocytes, but they exhibited visible striations and expressed N-cadherin and connexin 43, components of intercalated discs. What is the developmental origin of these putative cardiac progenitor cells? They may represent a developmental remnant from a multipotent mesodermal cell population that has persisted in the heart throughout embryonic and postnatal development or, alternatively, itinerant bone marrow–derived cells that are mobilized in response to myocardial injury. In support of the latter hypothesis, transplantation of GFP-labeled, c-Kit+ bone marrow–derived mononuclear cells into sublethally irradiated wild-type adult mice revealed that c-Kit+ cells in the adult injured heart are derived mostly from the transplanted marrow cells. Concomitantly with the study by Beltrami et al, Oh and colleagues isolated another resident population of putative adult cardiac progenitor cells characterized by the expression of stem cell antigen (Sca)-1. Sca-1+ cells express several early cardiac transcription factors including GATA4 and Mef2, as well as telomerase reverse transcriptase, which has been associated with the potential for self-renewal. However,
they do not express Nkx2.5 or genes encoding cardiac sarcomeric proteins. Although these cells do not spontaneously differentiate in vitro into cardiomyocytes, treatment with the genome-wide demethylating agent 5-azacytidine\textsuperscript{27,29} or oxytocin\textsuperscript{29} for 4 weeks generated a small subpopulation of cells (<5%) that expressed the cardiac transcription factor Nkx2.5 and cardiac contractile proteins. Phenotypically, sarcomeric proteins were demonstrated not only biochemical differentiation, as evidenced by the expression of sarcomeric transcription factors and proteins, but also functional cardiac differentiation, as determined by sarcomeric organization, intracellular calcium transients, and cellular contraction.\textsuperscript{34} Although their clonogenic potential, capacity for self-renewal, and developmental origin remain to be determined, on coculture with adult rat ventricular cardiomyocytes, these cells demonstrate not only biochemical differentiation, as evidenced by the expression of cardiac transcription factors and contractile proteins, but also functional cardiac differentiation, as determined by sarcomeric organization, intracellular calcium transients, and cellular contraction.\textsuperscript{34}

Depending on the study examined, these 3 populations of adult cardiac progenitor cells (c-Kit\textsuperscript{+}, Sca-1\textsuperscript{+}, SP) represent

\begin{table}
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\caption{Characteristics of Resident Populations of Cardiac Progenitors and Stem Cells}
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
\textbf{Cell Type (References)} & \textbf{Frequency} & \textbf{Self-Renewal} & \textbf{Clonogenic} & \textbf{Multipotent} & \textbf{Markers} & \textbf{Differentiation Protocol} & \textbf{Functional Characterization} & \textbf{Effect After Transplantation} \\
\hline
Lin- c-Kit\textsuperscript{+} stem cells (22, 23, 45) & \textasciitilde1 per \(1 \times 10^6\) myocytes & Yes & Yes & Yes & +c-Kit, Nkx2.5, Gata4, Met2 & Differentiation medium (8 days) plus intracardiac injection & +Endothelial proteins & Bands of regenerating myocardium and partial functional improvement following myocardial infarction \\
\hline
Sca-1\textsuperscript{+} stem cells (27–29, 53–55) & \textasciitilde3 per \(1 \times 10^5\) myocytes & Unknown & Unknown & Unknown & +Sca-1, Gata4, Nkx2.5, CD31 & 5-azacytidine or oxytocin (4 weeks) & +Nkx2.5 & Engraftment of Sca-1\textsuperscript{+} cells in the infarcted myocardium \\
\hline
Cardiac side population cells (32–35) & \textasciitilde1 per \(3 \times 10^6\) cardiac cells & Unknown & Unknown & Unknown & +Abcg2/Mdr1, Sca-1, Met2a/c & Coculture with adult cardiomyocytes (2–3 weeks) & +Endothelial proteins & Bands of regenerating myocardium and partial functional improvement following myocardial infarction \\
\hline
Cardiospheres (46–50) & Unknown & Yes & Yes & Yes & +c-Kit, Sca-1, Fkappa1, vWF, CD31, CD34, CD90, CD105 & Intracardiac injection & +SM proteins & Unknown \\
\hline
Isl1\textsuperscript{+} progenitors (92–93) & 500–600 per rat heart & Yes & Yes† & Yest & +Isl1, Nkx2.5, Gata4, c-Kit, Sca-1, Tbx5 & Coculture with neonatal cardiomyocytes (3–5 days) & +SM proteins & Unknown \\
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0.005% to 2% of the total cellular content in the heart, enter the cell cycle when growth of the heart is attenuated, proliferate in culture, and form cells expressing cardiomyogenic markers. They appear phenotypically distinct from one another and show differential expression of surface markers. In some instances, long-term culture of these cells is required to generate sufficient cell numbers for experimentation, raising concern that phenotypic drift could arise as an artifact of in vitro culture. Furthermore, differences in the experimental approaches and readouts used in these various studies have contributed to discrepancies in defining the relative cardiomyogenic potential of resident cardiac progenitor cells. To date, the exact lineage relationships between these adult cardiac progenitor cell populations and embryonic cardiac progenitor cells remain unknown. Despite these questions, injection of adult cardiac stem cells directly into infarcted mouse or rat myocardium has been reported to provide short-term improvement in heart function. It is possible that the reported functional improvement is attributable to a prosurvival paracrine effect or enhanced angiogenesis. Indeed, clinical trials using bone marrow–derived stem cell infusions into patients with myocardial infarction have suggested that paracrine factors may be responsible for the transient improvement in cardiac function in humans.

**Cardiac Progenitors in the Human Adult Heart**

The presence of endogenous cardiac progenitors in the rodent adult heart has prompted studies into whether similar populations exist in the human adult heart. As was demonstrated in rodents, a heterogeneous population of cardiac cells defined by the expression of the primitive stem cell markers c-Kit, MDR1, or a Sca-1–like epitope could also be found in human cardiac specimens from patients with aortic stenosis, myocardial infarction, and in the postmortem hearts of patients who had undergone cardiac transplantation. These cells lacked early indicators of bone marrow cell differentiation and did not express markers of differentiated cardiomyocytes, smooth muscle, fibroblasts, or endothelial cells. When isolated by fluorescence-activated cell sorting, the human cardiac c-Kit+ subset was reported to give rise to cardiomyocytes, vascular smooth muscle cells, and endothelial cells in vitro, and following transplantation into immunodeficient mice.

Concurrently, Messina et al described the isolation of a heterogeneous population of cells from human atrial and ventricular surgical biopsy specimens that form clonal, multicellular spherical clusters in suspension culture termed "cardiospheres." Cardiospheres contain cells positive for c-Kit, Sca-1, and the KDR (kinase insert domain receptor), are capable of long-term self-renewal, and appear to give rise to both endothelial and smooth muscle cell types. When cocultured with neonatal rat cardiomyocytes, they form beating clusters. Cardiosphere-derived cells have more recently been isolated with improved efficiency from endomyocardial right ventricular biopsies of adult patients, approaching cell numbers that would be required for transplantation. To date, transplantation studies in postinfarct pigs and SCID mice show short-term improvements in cardiac function, likely mediated by paracrine effects of the injected cells, because few surviving cells can be identified beyond 3 weeks of transplantation.

The lack of known cell surface markers specific to cardiac progenitors has raised questions regarding the cardiac specificity of the currently described adult cardiac progenitor cells. Pouly et al reported that at least some of the c-Kit+ cells found in human adult heart specimens may in fact be mast cells, based on immunohistochemical staining of endomyocardial biopsy and right atrial appendage samples. Colocalization experiments demonstrated that all the c-Kit+ cells they isolated from heart biopsies stained positive for leukocyte common antigen (CD45), suggesting hematopoietic origin. Their perivascular location and expression of c-Kit suggested that these cells could be mast cells. This phenotype was subsequently confirmed by positive staining for tryptase, an enzyme specific to mast cells. Additionally, multiple groups have identified cells with the capacity to proliferate and form cardiomyocytes in adherent cell culture on the basis of their ability to bind an antimouse Sca-1 antibody. Sca-1, however, is not a known determinant on human cells, a detail that has sparked debate as to their legitimacy as cardiac progenitors. To date, there is no consensus on the best marker for identification of adult cardiac stem cells, and the molecular mechanisms promoting their self-renewal and differentiation into the various lineages of the heart are largely unknown. Ultimately, in vivo lineage tracing studies in animal models will be required to validate any putative cardiac stem/progenitor cell population both during normal aging and in the setting of cardiac injury.

**Origins of Cardiac Progenitors in the Developing Heart**

Recent advances in conditional gene-targeting techniques and the availability of tissue specific enhancers and promoters have allowed us to track the stepwise commitment of cardiac progenitor cells and their intermediates before their terminal differentiation. Such in vivo genetic fate mapping has increasingly been used to identify novel stem cells and related progenitors and has contributed significantly to our understanding of cell lineage diversification within the heart. Until recently, the formation of cardiac, smooth muscle, and endothelial cell lineages in the heart had largely been ascribed to distinct populations of embryonic precursors. Early lineage-tracing studies in avian model systems suggested that a common muscle cell precursor exists for both the working myocardium and the conduction system. Likewise, another common progenitor, the hemangioblast, was found to give rise to endothelial and blood cell lineages, a finding indicating that a common precursor might also exist for endothelial cells in the heart. Recently, a growing body of evidence from multiple independent laboratories instead suggests the existence of a common multipotent precursor for the diverse muscle and nonmuscle lineages of the heart. This clonal model of heart lineage diversification implies a stem cell paradigm for the generation of the diverse cardiovascular cell types, similar to that of hematopoiesis, where a single stem cell is able to reconstitute the...
entire hematopoietic system through extensive self-renewal and subsequent multilineage differentiation.66,67

It is generally accepted that all vertebrates follow a similar developmental paradigm in which pluripotent cells undergo germ layer commitment to become further differentiated into organ fields as development proceeds. The earliest precursors for heart-forming cells form in the vertebrate mesoderm68 and after entering the precardiac mesoderm stage of development, transition from expressing the T-box transcription factor brachyury T (Bry) to expressing mesoderm posterior (Mesp)1.69,70 As these early cardiac mesodermal cells contribute to the developing heart, their transcriptional program determines the lineage specification that will follow. Mesp1+ cells encompass all cardiac progenitor cells, but have not yet

to the atria, outflow tract (OT), and right ventricle (RV). Epicardial progenitors (green) also contribute to a minor portion of cardiomyocytes in all 4 heart chambers.

Figure 1. Embryological contributions to mammalian heart development. The heart primordium is first recognizable as the cardiac crescent (left), a structure derived from first heart field (FHF) (blue) cardiogenic precursors. The cells of the cardiac crescent join in the midline to form the linear heart tube, which undergoes right-ward looping to form the primitive chambers of the mammalian heart (middle). By this time, precursor cells that form in the second heart field (SHF) (red) have migrated into the rostral and caudal portions of the developing heart. In the postnatal heart (right), progenitors from the FHF contribute primarily to the atria (left [LA] and right [RA]) and the left ventricle (LV). SHF derivatives contribute mainly

Figure 2. Proposed cellular hierarchy of cardiac progenitor cells and their lineage diversification. Precursors for heart-forming cells in the vertebrate mesoderm transition from expressing brachyury T to Mesp1 when they enter the precardiac mesoderm stage of development. As these early cardiac mesodermal cells contribute to the developing heart, their transcriptional program determines their further lineage specification. Within the second heart field, Isl1, together with Nkx2.5 and Flk1, defines multipotent Isl1+ cardiovascular progenitor cells that can give rise to myocardial, conduction system, smooth muscle, and endothelial lineages. A subset of precursors derived from Isl1+ progenitors may function as more restricted bipotent progenitors, displaying myocardial and smooth muscle potential or endothelial and smooth muscle potential. The developmental potential of the first heart field progenitors is largely uncharacterized. Epicardial progenitor cells are marked by Wt1 and/or Tbx18. These cells have been shown to give rise to cardiomyocytes, smooth muscle, endothelial cells, and fibroblasts in the heart. CD31 (PECAM 1) indicates platelet/endothelial cell adhesion molecule; cTnT, cardiac troponin T; DDR2, discoidin domain receptor 2; FHF, first heart field; HCN4, potassium/sodium hyperpolarization-activated cyclic nucleotide-gated channel 4; SHF, second heart field; sm-actin, smooth muscle actin; smMHC, smooth muscle myosin heavy chain. (Illustration Credit: Cosmocyte/Ben Smith).
committed to the cardiac fate, as some also give rise to derivatives of the paraxial mesoderm and skeletal muscle of the head and neck.71 During their migration, Mesp1+ cardiac precursor cells expand rapidly, ultimately segregating into 2 spatially and temporally distinct cardiogenic heart fields exhibiting unique time courses of differentiation and distinct regional contributions to the embryonic heart. It is at this stage that heart precursor cells commit irreversibly to the cardiac lineage and become cardiac progenitor cells expressing key cardiac transcription factors such as GATA4, Nkx2.5, and Islet-1 (Isl1).

The first population of cells to migrate to the heart-forming region, referred to as the first, or primary, heart field originates bilaterally in the anterior splanchnic mesoderm and gives rise to a group of cardiovascular progenitors that form the cardiac crescent (Figure 1). The cardiac crescent goes on to fuse in the midline, forming the linear heart tube, and ultimately gives rise to the majority of the left ventricle, the atrioventricular canal, and parts of the atria.72 The second, or anterior, heart field appears in the extracrescent tissue and is largely derived from a population of cells located dorsal and anterior to the heart tube in the pharyngeal and splanchnic mesoderm. As the linear heart tube elongates and undergoes right-ward looping, cardiovascular progenitors from the second heart field migrate into the heart tube, contributing cells that will form the main parts of the atria, the right ventricle, and the outflow tract myocardium.73–76

The heart subsequently receives important contributions from 2 additional sources, the cardiac neural crest and the proepicardium. Cardiac neural crest cells contribute to normal development of the outflow tract and great vessels, as well as to essential components of the cardiac autonomic nervous system.77,78 Proepicardial cells migrate onto the surface of the heart, giving rise to the epithelial sheet of cells known as the epicardium. Some epicardial cells undergo an epithelial-to-mesenchymal transformation and migrate into the subjacent myocardium, contributing to the development of coronary smooth muscle and to the surrounding cardiac fibroblasts of the interstitium and adventitia.79–83 Recently, the epicardium has also been shown to be a source of cardiomyocytes.84,85 In addition to contributing to the cellular makeup of the heart, the epicardium and myocardium mutually engage in both paracrine and direct cellular interactions that are required for the growth and development of each compartment.86–89

Heart Field Progenitors in Cardiac Development
Lineage tracing experiments in mice have demonstrated that most of the early second heart field myocardial, smooth muscle, and endothelial cells can be traced to multipotent heart progenitors that express the LIM-homeodomain transcription factor Isl1 (Figure 2).64,76,90 Isl1 is transiently expressed in cardiac mesoderm, and although it is not strictly cardiac-specific, its expression has been used to identify cardiac progenitor cells because its downregulation coincides with the expression of terminal cardiac differentiation markers.76 Using genetically labeled embryonic stem (ES) cells for the Isl1 lineage, Moretti et al showed that ES cell–derived Isl1+ progenitors can differentiate into the above 3 cardiac lineages after a brief period of in vitro expansion on a mesenchymal feeder layer.64 Evidence supporting the possibility that human ISL-1+ cardiac progenitors are multipotent has also been provided by their isolation from human ES cells followed by in vitro differentiation.91 Additional studies in the mouse embryo have confirmed that Isl1+ cardiovascular progenitors contribute to all cells in the right ventricle, to portions of the atria, ventricular septum and conduction system, and to a minor proportion of the left ventricular free wall which is derived largely from first heart field progenitors.84,76,92 Notably, a subset of Isl1+ undifferentiated progenitors remains embedded in the embryonic heart after its formation and a few cells are still detectable shortly after birth in the compartments that arise from Isl1+ second lineage precursors during cardiac development.92,93 Unlike the other putative resident cardiac progenitor populations discussed previously, these cells do not express c-Kit or Sca-1, although they do express Nkx2.5 on differentiation. Their ability to self-renew in vitro on a cardiac mesenchymal feeder layer and to be stimulated to differentiate into fully mature functional cardiomyocytes, with electrophysiological characteristics of fully differentiated cardiomyocytes including responsiveness to β-adrenergic agonists, indicates that these cells may represent remnant cardiac progenitors from their embryonic Isl1+ precursors.

Concurrent with these Isl1 studies, we reported the isolation of a bipotent myocardial and smooth muscle cardiac progenitor cell population from mouse embryos and differentiated ES cells using a cardiac-specific enhancer element of the homeobox transcription factor gene Nkx2.5, a marker expressed in both the first and second heart fields.63 Nkx2.5+ cells obtained from ES cultures display high proliferative capacity and express modest levels of the stem cell markers c-Kit and Sca-1, but do not express endothelial markers, suggesting that the endothelial and myogenic lineages are largely segregated by the time Nkx2.5 is expressed. However, other lineage tracing studies in mice have shown that some, if not the majority, of the endocardial cells are descendants of embryonic Nkx2.5 progenitor cells.94 Furthermore, genome-wide transcriptional analysis demonstrated that embryo-derived Nkx2.5 progenitor cells express vascular-endothelial markers, a finding that further supports residual capacity for endothelial differentiation in Nkx2.5+ cells.95 Whether the Nkx2.5+ progenitors,63 and the previously mentioned Isl1+ progenitors,64 represent completely distinct populations or descendants from a common progenitor remains to be fully determined. Further lineage tracing experiments using cells doubly marked for Isl1 and Nkx2.5 will help to rigorously define the relationship between these populations.

To date, it has not been possible to isolate and characterize the developmental potential of purified populations of primary heart field progenitors because of an absence of molecular markers unique to that field. The identification of specific sets of markers for the first and second heart field lineages would be extremely valuable, as it is unclear whether cardiac regeneration of the left ventricle, a first heart field–derived structure, will require purified populations of first heart field progenitors. Furthermore, although it has been postulated that a common primordial cardiovascular progenitor that gives rise to progenitors for both the first and second
heart fields exists, the identity of such common progenitor remains elusive.

Evidence for the existence of such a common progenitor comes from studies using retrospective clonal analysis, as well as genetic fate mapping experiments. Studying the in vitro differentiation of mouse ES cells, Kattman et al labeled cells positive for Bry, as well as fetal liver kinase (Flk)1, the cell surface receptor that encodes the VEGFR2 (vascular endothelial growth factor receptor 2), to identify a heterogeneous population of cells that exhibited cardiomyogenic potential. On ES cell differentiation, 2 distinct waves of Bry−/Flk1− cells were identified within the developing embryoid body. The first wave of Bry−/Flk1− cells contributed to the hemangioblast, a population of mesodermal differentiated cells that contribute precursors to the hematopoietic and vascular compartments. The second wave of Bry−/Flk1− cells contained clones with cardiomyocyte, vascular smooth muscle, and endothelial potential. Some colonies became positive for the second heart field marker Is1, whereas others were negative for Is1, but expressed Tbx5, a T-box transcription factor associated with derivatives of the first heart field. Similar findings have since been replicated using human ES cells in a parallel set of experiments, where a population of progenitor cells positive for KDR (kinase insert domain receptor), the human ortholog of Flk1, have been shown to display cardiac, endothelial, and vascular smooth muscle potential in vitro and, following transplantation, in vivo. Taken together, these experiments point toward a common early progenitor that gives rise to the first and second heart field lineages.

**Epicardial Progenitors in Cardiac Development**

Along with the 2 heart fields, the importance of the proepicardial organ and epicardium to cardiovascular development and cell specification has become increasingly appreciated in recent years. Under defined conditions, adult epicardial cells derived from rodents and humans can undergo epithelial-to-mesenchymal transformation, migrating into the subjacent myocardium to differentiate into smooth muscle and endothelial cells. Interestingly, 2 independent studies have recently drawn attention to a previously unrecognized role of epicardial derivatives in cardiogenesis, providing evidence for the existence of an epicardium-derived cardiac progenitor cell population (Figures 1 and 2). These progenitors are marked by the transcription factors Wt1 (Wilms’ tumor protein) and/or Tbx18, although the use of Tbx18 to uniquely label epicardial progenitor cells has recently been challenged because concomitant myocardial Tbx18 expression was found to be present. These cells not only contribute to cardiomyocytes in all 4 chambers of the adult mouse heart, but may also have multipotent potential, as some Tbx18+ clones from mouse embryos are able to give rise to both cardiomyocytes and smooth muscle cells under defined culture conditions. What is the relationship between epicardium-derived cardiac progenitors and other embryonic progenitors? Fate mapping experiments performed by Zhou et al found evidence for a robust contribution from Nkx2.5+ and Is1+ precursors to Wt1+ proepicardial cells, positioning the Wt1+ proepicardial lineage as an early branch from the multipotent Nkx2.5+/Is1+ progenitor lineages. However, proepicardial cells do not actively express either Nkx2.5 or Is1, suggesting that these markers and Wt1 are either transiently coexpressed or sequentially expressed earlier in development. Supporting this possibility, in an ES model system, Zhou et al were able to document transient coexpression of Wt1 with Nkx2.5 in ES derived cardiac progenitors. In contrast to the Wt1+ progenitors, Cai et al found little overlap between Tbx18 and Is1 lineages in the embryo, suggesting that Tbx18 and Is1 are, at least in part, distinct cardiac progenitor populations and contribute in a complementary fashion to heart formation.

Although epicardial progenitors theoretically provide an attractive population of cells to be used in cardiac regeneration or repair, their ability to produce functional cardiomyocytes in an infarcted heart remains to be demonstrated. In zebrafish, the epicardium promotes cardiac regeneration by invading the wound site and creating a dense vascular network. Therefore, it is possible that the greatest contribution of the epicardium to cardiac regeneration lies not in its ability to deliver new cardiomyocytes to the injured myocardium, but in its ability to promote endogenous cardiac progenitor cell expansion and neovascularization by paracrine signaling to surrounding cells. Future research on the regenerative role of epicardium-derived progenitors should include an assessment of both the ability of the epicardium to directly contribute cardiomyocytes and its role in mediating paracrine effects.

**Applications of Cardiac Progenitors**

For cardiac progenitor cells to play a significant role in the field of cardiac regenerative medicine, they will need to be recruited or transplanted to the site of injury in sufficient numbers and directed to differentiate into fully mature and functional cardiomyocytes (Figure 3). One strategy to approach the challenge of obtaining sufficient quantities of cells needed for transplantation is to derive cardiac progenitors from pluripotent ES cells that represent an expandable and renewable source of multiple progenitors. ES cells can be directed by a variety of methods to undergo stepwise differentiation to mesoderm and then to cardiac progenitors, and in this regard have been instrumental in characterizing cardiac progenitor populations during the early stages of development and lineage commitment, which are difficult to study in the embryo. Importantly, ES-derived cardiomyocytes not only share molecular markers with native cardiomyocytes, but ultrastructural, electrophysiological, and mechanical studies of ES cell progeny indicate that they also exhibit all the hallmarks of cardiomyocytes. Nonetheless, ES-derived cardiomyocytes exhibit less organized sarcomeric structures than adult cardiomyocytes, a phenotype reminiscent of immature cardiomyocytes. The issue of cellular maturation will need to be addressed if ES-derived cardiomyocytes are to be used in therapeutic applications to promote contractility in the failing heart.

Recently, much excitement has been generated by the discovery that human somatic cells, through the ectopic expression of 3 or 4 defined transcription factors, can be reprogrammed into induced pluripotent stem (iPS) cells,
exogenous cardiac progenitor cells, or promote cardiac progenitor triggers cardiac lineage-specific differentiation of endogenous or tors, either in vitro or in vivo, may enhance cardiomyocyte survival, tion of an engineered tissue graft. The addition of extracellular fac-
could be directly implanted into the heart or used for the genera-
differentiation into cardiac progenitors. Following expansion, they
progenitors/cardiomyocytes or by generating iPS cells followed by
own somatic cells either directly (ie, transdifferentiation) into cardiac
progenitor cells. Apart from their potential application in regener-
cells or isolated from cardiac biopsy specimens. Alternat-
they could be generated by reprogramming a patient’s own somatic cells either directly (ie, transdifferentiation) into cardiac
progenitors/cardiomyocytes or by generating iPS cells followed by
differentiation into cardiac progenitors. Following expansion, they
could be directly implanted into the heart or used for the gener-
ation of an engineered tissue graft. The addition of extracellular fac-
tors, either in vivo or in vitro, may enhance cardiomyocyte survival,
trigger cardiac lineage-specific differentiation of endogenous or
exogenous cardiac progenitor cells, or promote cardiac progenitor
and/or cardiomyocyte proliferation.

Figure 3. Strategies for delivering cardiac cell therapy. Con-
ceptually, cardiovascular progenitor cells could be derived from
human ES cells or isolated from cardiac biopsy specimens. Alterna-
tively, they could be generated by reprogramming a patient’s own somatic cells either directly (ie, transdifferentiation) into cardiac
progenitors/cardiomyocytes or by generating iPS cells followed by
differentiation into cardiac progenitors. Following expansion, they
could be directly implanted into the heart or used for the genera-
tion of an engineered tissue graft. The addition of extracellular fac-
tors, either in vitro or in vivo, may enhance cardiomyocyte survival,
trigger cardiac lineage-specific differentiation of endogenous or
exogenous cardiac progenitor cells, or promote cardiac progenitor
and/or cardiomyocyte proliferation.

exhibiting all of the cardinal features of pluripotent ES
cells. Apart from their potential application in regener-
medicines, patient-derived iPSCs may be particularly
useful for bedside-to-bench research by allowing for the cre-
ation of disease-specific cell lines for which animal model
systems are either lacking or inadequate. The use of
autologous, patient-derived iPSCs for regenerative pur-
purposes would circumvent issues related to immunocompatibil-
and bypass many of the ethical considerations associated
with generating ES cell lines. The original practice of virally
inserting genes into human somatic cells has also been
recently overcome, eliminating concerns regarding the poten-
tial hazards of viral integration into the human genome. Despite these potential advantages, patient-specific iPSC cell
lines require weeks if not months to generate and also differ
epigenetically from ES cells, a distinction which may inter-
fere with their ability to form mature, functional cardiomyo-
cells. The use of pluripotent stem cells, such as ES and
iPS cells, also poses a significant risk of teratoma formation
unless the progenitor cells can be isolated with an exceptional
degree of purity, a task that has not been satisfactorily
achieved with any pluripotent stem cell lineage thus far.

Although the identification of human cardiac progenitor
cell-specific surface markers would help to overcome this
issue, to date, no single surface marker has been identified
that readily distinguishes cardiac progenitors from other
differentiated progenies or their pluripotent precursors. One
solution to overcome this challenge is to directly reprogram
exogenous cells such as fibroblasts to a relatively restricted
mesodermal or cardiac-restricted progenitor state through
induced expression of a defined set of cardiogenic transcription factors. This strategy has already been used successfully
to generate pancreatic cells, functional neurons, and cardiomyocytes. Induced expression of 2 cardiac transcription factors, Gata4 and Tbx5, has been used to direct mesoderm to
cardiomyocytes, and the combination of Gata4, Tbx5, and Mef2c can direct reprogramming of cardiac or dermal fibroblasts into cells that very closely resemble
adult cardiomyocytes. Importantly, the reprogramming of
fibroblasts directly to cardiomyocytes does not appear to
proceed via dedifferentiation to a progenitor cell state, per-
haps explaining why transcription factors associated with
cardiac progenitors such as Is11 and Nkx2.5 are not required
for induction of this process. Further validation of this
reprogramming approach to generate autologous cardiomyo-
cyes should help to simplify purification procedures required
for cell transplantation because potentially fewer harmful
contaminating cells would be involved.

Other unique challenges in cardiac regenerative medicine
include the assembly of differentiated cardiac cells into the
specific 3D structures of the mature heart. In the ventricle, a
complex alignment of cardiac myocytes exists designed to
create the high degree of force generation needed to propel
blood rapidly out of the heart during systole. Cardiomyocytes
must also be coupled to each other by intercalated disks
whose gap junction proteins facilitate spreading of the elec-
tric impulse from one fiber to another. To improve cardiac
function and prevent arrhythmogenesis, transplanted cells
will have to stably engraft, align, and couple with the
myocardium of the host in a coordinated fashion. Given the
architectural complexity required, a bioengineered tissue
graft may be the most ideal way to introduce regenerating
cardiomyocytes to the injured heart.

Perspectives

Although achieving meaningful cardiac regeneration in pa-
patients may not yet be feasible, incremental advances in our
understanding of developmental and stem cell biology con-
tinue to move medical science closer toward this noble goal.
Along the way, some of our most basic premises underlying
cardiac development and cardiomyocyte renewal are being
redefined. Dissecting the biologically complex roles of car-
diac progenitor cell populations, both in cardiogenesis and in
regeneration, will require a complete understanding of the
developmental logic that accounts for the establishment of the
diverse cell lineages within the heart. In this respect, devel-
oping a detailed human cardiovascular cell lineage map, with the molecular markers needed to identify and purify distinct cell populations with cardiogenic potential, is an important step in the right direction. Meanwhile, we anticipate that many of our existing paradigms and dogmas will be unlearned before cardiac regeneration becomes a clinical reality.

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