Abstract: The ability of pluripotent stem cells to self-renew and differentiate into all somatic cell types brings great prospects to regenerative medicine and human health. However, before clinical applications, much translational research is necessary to ensure that their therapeutic progenies are functional and nontumorigenic, that they are stable and do not dedifferentiate, and that they do not elicit immune responses that could threaten their survival in vivo. For this, an in-depth understanding of their biology, genetic, and epigenetic make-up and of their antigenic repertoire is critical for predicting their immunogenicity and for developing strategies needed to assure successful long-term engraftment. Recently, the expectation that reprogrammed somatic cells would provide an autologous cell therapy for personalized medicine has been questioned. Induced pluripotent stem cells display several genetic and epigenetic abnormalities that could promote tumorigenicity and immunogenicity in vivo. Understanding the persistence and effects of these abnormalities in induced pluripotent stem cell derivatives is critical to allow clinicians to predict graft fate after transplantation, and to take requisite measures to prevent immune rejection. With clinical trials of pluripotent stem cell therapy on the horizon, the importance of understanding immunologic barriers and devising safe, effective strategies to bypass them is further underscored. This approach to overcome immunologic barriers to stem cell therapy can take advantage of the validated knowledge acquired from decades of hematopoietic stem cell transplantation. (Circ Res. 2013;112:549-561.)

Key Words: embryonic stem cells ■ immunogenicity ■ induced pluripotent stem cells ■ patient-specific therapy ■ stem cell therapeutics ■ tolerance ■ transplantation
Pluripotent stem cells can differentiate into cell types of the 3 primary embryonic germ layers and therefore have extraordinary potential for regenerative medicine. Thomson et al and Reubinoff et al pioneered the development and differentiation of human embryonic stem (ES) cell lines more than a decade ago. After their discovery, these cells have been under going intense investigation as a source of functional cells to augment damaged tissue function and to treat degenerative diseases. In animal models, differentiated ES cells have demonstrated regenerative capabilities in treating spinal cord injury, diabetes mellitus, Parkinson disease, liver failure, and myelin disease. Pluripotent stem cells also have generated great excitement for cardiovascular regenerative medicine, because they can be differentiated to functional cardiomyocytes and, as a part of biological pacemakers, can be grafted into injured myocardium. Despite these promising results, immunologic constraints associated with the transplantation of pluripotent stem cell derivatives have not been adequately addressed and remain one of the greatest obstacles to cell replacement therapy.

It was originally thought that pluripotent stem cells would be capable of evading immune surveillance and rejection because of their low expression of major histocompatibility complex (MHC) class I, MHC class II, and costimulatory molecules, and because of the expression of immunomodulatory molecules, such as perforin-deactivating Serpin-6 (endogenous inhibitor of granzyme B) and transforming growth factor-β, which both inhibit T-cell proliferation. However, this initial enthusiasm was dampened by evidence that pluripotent stem cells do elicit a donor-specific immune response in immunocompetent mice. Transplanted allogeneic and xenogeneic ES cells and their derivatives are not immune-privileged and therefore may encounter the same immunologic barriers as any other grafts.

In an effort to minimize immunologic rejection of transplanted ES cell derivatives, Taylor et al devised a strategy to create a human ES cell bank from donated surplus embryos with sufficient human leukocyte antigen (HLA) diversity to provide a HLA match for a reasonable percentage of the population in the United Kingdom. They predicted that a bank of 150 human ES cell lines would provide a full match at HLA-A, HLA-B, and HLA-DR for 20% of potential recipients; a beneficial match (defined as 1 HLA-A or 1 HLA-B mismatch only) or better for 37.9% of recipients; and an HLA-DR match or better for 84.9% of recipients (Figure 1). The results were calculated based on criteria used clinically for kidney and heart transplantation in which matching of blood group and matching of 3 of 9 MHC loci are considered sufficient and acceptable. Predictions such as these, however, have limited clinical value, and it remains unclear what level of disparity in MHC loci would warrant acceptance vs rejection of stem cell–derived grafts in humans. Moreover, recent research has indicated that matching MHC molecules alone is insufficient to guarantee tolerance to in vitro differentiated ES cells, because variance at the minor histocompatibility loci alone has been shown to induce rejection. A better understanding of how varying levels of compatibility elicit varying levels of immune responses to pluripotent stem cells and their derivatives in vivo is required to validate or revise cell line banking predictions, and would further aid in the progression of stem cell therapy toward clinical translation. Here, we review current knowledge of the immunogenicity of pluripotent stem cells and their progenies, discuss mechanisms of graft rejection, and present possible strategies to prevent immunologic rejection.

**Hope for Immunocompatible Pluripotent Stem Cell Therapy**

Hurdles associated with ES cell–based therapy have led to an interest in a more readily accessible alternative with potential
to be immunologically matched to the recipient. In 2006, Takahashi and Yamanaka narrowed a list of transcription factors overexpressed in ES cells to the following 4 factors: octamer-binding transcription factor 4 (Oct4); sex determining region Y-box 2 (Sox2); Krueppel-like factor 4 (Klf4); and c-myelocytomatosis viral oncogene homolog (c-Myc). When expressed retrovirally, these transcription factors were capable of reprogramming fibroblasts to an embryonic-like state.\textsuperscript{20,25} Known as induced pluripotent stem (iPS) cells, they have revolutionized the field of stem cell research by demonstrating somatic cell plasticity and by offering an appealing solution to the problem of immune rejection for stem cell–derived therapeutics. The derivation of ES-like cells from somatic tissues ignited the possibility of pursuing exciting avenues for patient-specific cell therapy, and as a platform for drug screening and disease modeling.\textsuperscript{22–24} Moreover, these cells represent a possible solution to the ethical objections that have been raised against the use of human ES cells.

Initial studies examining the biology of iPS cells compared with ES cells showed that they have similar morphology, proliferation, surface antigens, gene expression, epigenetic status of pluripotent cell–specific genes, and telomerase activity.\textsuperscript{20,25} Nevertheless, a rapidly accumulating body of work suggests that considerable differences exist between these 2 pluripotent cell types, including important aspects such as their global gene expression,\textsuperscript{26} single cell transcription signature,\textsuperscript{27} epigenetic landscape,\textsuperscript{28,29} genomic imprinting,\textsuperscript{30} and somatic mutations.\textsuperscript{31} These deficiencies represent a significant hurdle to the clinical value of iPS cells as therapeutics. For example, genomic alterations acquired during the reprogramming of somatic cells and also during the differentiation of iPS cells to a desired cell type not only may increase the tumorigenicity of these cells\textsuperscript{32} but also may also generate potentially immunogenic neoantigens that could elicit immune responses even in a MHC-matched context.\textsuperscript{33} In support of this premise, a recent study has demonstrated that iPS cells have a high incidence of duplications on chromosome 12,\textsuperscript{34} resulting in significant enrichment of cell cycle–related genes. Such aneuploidy may affect the differentiation capacity of iPS cells, and also may increase their tumorigenicity and possibly their immunogenicity.\textsuperscript{31}

Very limited research has been performed to determine whether clinically relevant therapeutic cells derived from autologous iPS cells are nonimmunogenic or whether they possess some level of autogenicity (ability of a particular autologous substance to provoke an immune response in the body of a human or animal). If proven autogenic, then the high costs and the length of time needed to produce adequate quantities of patient-specific iPS cell–derived therapeutics may not justify their use over allogeneic ES or iPS cells. As more systematic investigations into the immunobiology of iPS cells begin, the goal of bypassing immunologic barriers, even when transplanted autologously, remains only a possibility rather than a reality. The recent demonstration by Zhao et al\textsuperscript{35} that mouse iPS cells are rejected in syngeneic recipients suggests that stringent screening for incompatibilities between the donors and recipients of stem cell–derived cellular therapeutics may be required for transplantation of not only allogeneic cells but also autologous cells. Reassurance to the value of iPS cells came with recent evidence that reprogramming causes fewer mutations than previously thought,\textsuperscript{36} and that skin and bone marrow from chimera mouse derived from iPS cells elicited negligible immunogenicity in syngeneic recipients.\textsuperscript{37}

### Immunogenic Molecules of Pluripotent Stem Cells

**Major Histocompatibility Antigens**

The MHC, termed HLA in humans, consists of glycoproteins encoded by highly polymorphic genes on chromosome 6 that are codominantly expressed on the surface of almost all vertebrate cells. MHC encodes the main molecular targets of allograft rejection and MHC-associated incompatibilities between donors and recipients are responsible for almost all acute rejection. MHC is critical for the development of an adaptive immune response against pathogenic and foreign antigens because it contains a groove into which the antigen binds and is presented to T cells. In most species, each class of MHC is represented by >1 locus (polygeny). In humans, the class I loci are HLA-A, HLA-B, and HLA-C, which are expressed on every nucleated somatic cell. The class II loci, including HLA-DR, HLA-DQ, and HLA-DP, are expressed mostly on antigen-presenting cells (APCs) such as dendritic cells and macrophages. It is unclear why T cells should ever recognize foreign HLA molecules as they do in an allogeneic transplantation setting, but an estimated 1% to 10% of the T-cell pool can react with intact allogeneic HLA during direct T-cell allorecognition. As with any other tissue type, histocompatibility seems to be an important factor in the rejection of undifferentiated ES cells. ES cell rejection is accelerated when MHC molecules are upregulated during differentiation.\textsuperscript{38} during interferon-γ stimulation,\textsuperscript{39} or after teratoma formation.\textsuperscript{9,17,40–42} These results suggest that ES cells and potentially their progeny can become more immunogenic if transplanted into an environment that promotes upregulation of MHC (eg, inflammatory environment). HLA matching as a criterion for transplantation of stem cell–derived grafts may reduce the possibility of eliciting an immune response but may not be sufficient to promote graft acceptance. Manipulation of HLA expression on stem cells recently has shown promise as a strategy for generating hypoimmunogenic grafts.\textsuperscript{43} The same strategy has been used previously to facilitate transplantation of hematopoietic stem cells (HSCs).\textsuperscript{44} The clinical applicability of this strategy, however, remains questionable because it requires genetic manipulation to knock down a gene and may lead to the introduction of genetic variations. Knocking down HLA is yet another double-edged sword because it can increase the susceptibility of cells to natural killer (NK) cell–mediated killing.\textsuperscript{45–47}

**Minor Histocompatibility Antigens**

Identical HLA phenotype is not sufficient to guarantee graft survival. The role of non-HLA histocompatibility antigens such as minor histocompatibility antigens (mHA) in the context of immunologic rejection of pluripotent stem cells and their derivatives remains murky. mHAs are peptides derived from normal cellular proteins that show polymorphism among related and unrelated individuals and, when transplanted, can be sufficiently antigenic to induce cluster
of differentiation (CD)4+ and CD8+ T cells alloresponses.48,49 The importance of miHA in human transplantation is proven by the observation that even MHC-identical sibling pairs can develop T-cell-mediated graft failure,50 severe graft-versus-host disease,51,52 and graft-versus-leukemia effect.53 Robertson et al 19 transplanted murine ES cell–derived embryoid bodies in MHC-matched mice that differed in their expression of miHAs. They demonstrated that full concordance at the MHC loci between donor and recipient mice was insufficient to promote acceptance of murine ES cell–derived embryoid bodies because they were vigorously rejected at a rate similar to fully allogeneic embryoid bodies. In transplantation of ES cell–derived or iPS cell–derived therapeutics, natural miHA incompatibilities between donor and recipient may be accentuated by factors such as residual expression of embryonic antigens (eg, octamer-binding transcription factor 4)54 due to incomplete reprogramming and ectopic expression of miHAs acquired during reprogramming stress or during in vitro culture adaptation (Figure 2).32,33 Additionally, pluripotent stem cell–derived therapeutics may incorporate immunogenic miHA as a results of exposure to animal product–containing media or to media containing nonphysiological constituents. Epitopes derived from these incorporated neoantigens may augment immunogenicity.55 For example, prolonged culture of human ES cells in animal-free knockout serum and high ascorbate levels resulted in ectopic expression of CD30.56 Incompatible miHA peptides can be presented directly on self-MHC class I to CD8+ T cells that destroy the therapeutic graft or through APCs that process and present miHA peptides to T cells, eliciting an alloresponse.57 However, the extent and severity by which miHA will influence immune response against pluripotent stem cell–derived therapeutics remains to be determined. If proven important, then the optimization of culture conditions and reprogramming technique could prove crucial to the clinical translation of this technology. Also, the identification of potentially immunodominant miHA among pluripotent stem cell–derived progenies would facilitate screening for incompatibilities between donors and recipients and prediction of immunogenicity in vivo.

The ABO Blood Group
Primates express ABO blood group antigens that are displayed on the surface of red blood cells, epithelial cells, and vascular endothelial cells.58 Bacteria colonizing the gastrointestinal tract display carbohydrate structures that are similar to the oligosaccharide structures that comprise the ABO. To confer host protection against gastrointestinal bacteria, there is a natural production of IgM and IgG antibodies. These naturally occurring antibodies can cause antibody-mediated rejection of ABO-incompatible organ transplants. Limited studies have shown that human ES cells, as well as differentiated hepatocytes and cardiomyocyte-like cells,59 express ABO antigens.60 Therefore, the transplantation of an ABO-expressing stem cell–derived graft in an ABO-mismatched recipient could prompt an antibody-mediated hyperacute rejection by activating the complement cascade, thereby eliciting a complement-dependent target cell injury.61 Information about ABO expression in the various stem cell progenies is required before clinical translation. If proven to be important antigenic determinants, the use of therapeutics derived from human ES and iPS cells from blastocysts of blood group O should be prioritized.62

Killer Immunoglobulin-like Receptors
NK cells are key innate immune lymphocytes that play a critical role in recognizing self-MHC class I through a unique...
class of receptors called NK cell receptors. Although in an autologous setting NK cells can kill cells that express low HLA class I molecules, in an allogeneic environment they can kill cells that express HLA class I that are not recognized by their inhibitory killer immunoglobulin-like receptors (KIRs).\textsuperscript{63,64} The importance of the KIR family of NK cell receptors for transplantation and its role in the rejection of MHC-matched organs and cells are becoming increasingly evident, especially for HSC transplantation. The great variations in gene content, gene copy number, and allelic polymorphism within individual KIR genes result in significant diversity in KIR haplotypes among individuals. It remains to be seen whether KIR matching between donors and recipients will need to be considered before the transplantation of stem cell derivatives.

**Pluripotent Stem Cells Meet the Immune System: Pathways to Allorecognition**

The human immune system evolved in a hostile environment inhabited by pathogens and, consequently, has developed productive responses against both pathogens and foreign cells. The best-known cell types responsible for the direct killing of pathogenic cells are cytotoxic CD\textsuperscript{8+} T cells, also known as cytotoxic T lymphocytes, and NK cells. During an infection, both NK cells and CD\textsuperscript{8+} T cells are activated via antigen-specific receptors and by proinflammatory cytokines produced by auxiliary CD4\textsuperscript{+} T cells (also known as helper T cells) and APCs. The success of transplantation is largely limited by the activation of some of these same mechanisms. Cytotoxic T lymphocytes, helper T cells, and NK cells have been shown to hinder the survival of undifferentiated stem cells and ES cell–derived vascular progenitors in vivo,\textsuperscript{17,47,65} suggesting that these same mechanisms will pose an obstacle for stem cell–based therapy. However, the exact pathway leading to immune reactivity against these cells remains unknown.

The adaptive immune response is usually necessary and sufficient to reject allografts, and this also seems to be the case in rejection of stem cells and their cellular derivatives, where T cells emerge as pivotal players.\textsuperscript{17,19,38} Donor-derived MHC antigens expressed by an allograft almost always trigger T-cell allorecognition. T-cell receptor–mediated recognition of the MHC antigens can occur by 2 distinct pathways: (1) T cells recognize peptides complexed to donor MHC molecules displayed on the surface of the transplanted cells (direct pathway) or (2) T cells interact with processed donor-derived peptides bound to MHC molecules on self-APCs (indirect pathway; Figure 3).\textsuperscript{67,68} Increasing evidence supports the role of the indirect pathway in acute and chronic rejection of various grafts\textsuperscript{69,70} and in rejection of stem cells. Rejection of

![Figure 3](http://circres.ahajournals.org/). **Simplified schema exemplifying an immune response to a stem cell–derived cellular therapeutic.** Dendritic cells acquire antigens from the graft for presentation to T cells and natural killer (NK) cells, which mount specific responses after antigen receptor activation (signal 1). On T-cell receptor (TCR)–major histocompatibility complex (MHC) interactions, costimulation (signal 2) and proinflammatory cytokines (signal 3), such as interleukin-12 (IL-12) and type I interferons (IFNs), can promote the activation and clonal expansion of T cells. Similarly, resting NK cells also may receive signals via activating receptors (signal 2) and proinflammatory cytokine receptors (signal 3). Activated T cells and NK cells can generate cytotoxic responses against the graft, resulting in rejection. Figure adapted from Sun and Lanier.\textsuperscript{66}
pluripotent stem cells has been proposed to involve 3 main developmental stages. The first stage is intragraft delayed-type hypersensitivity, during which recipient MHC class II–restricted CD4+ T cells recognize alloantigens presented by recipient APCs and release graft-damaging proinflammatory cytokines. The second stage is cytotoxic T-lymphocyte response, during which self-restricted CD4+ T cells help generate cytotoxic T lymphocytes that can recognize intact allogeneic MHC class I molecules. The third stage is alloantibody response, during which alloantigen-primed CD4+ T cells deliver activating signals to B cells. However, considering the many layers of redundancy in the immune system, the pathways that lead to rejection may be diverse.

Although the direct pathway of allorecognition could be mitigated by eliminating APCs from the graft before transplantation72 certain types of pluripotent stem cell derivatives such as endothelial cells may elicit an immune response by interacting with T cells in an antigen-specific manner.72 Endothelial cells are capable of acting as nonprofessional APCs and, on upregulation of MHC class II molecules, can present antigens in a MHC-restricted fashion. Consequently, these cells can mediate the direct pathway of allorecognition. Such a pathway of allorecognition has been demonstrated to compromise the survival of certain allografts.73,74 Therapeutic use of ES cell–derived or iPS cell–derived endothelial cells will likely require addressing this pathway. This example underscores how the mechanisms leading to allorecognition may vary depending on the nature of the graft, further emphasizing the need for graft-specific strategies to adequately manipulate the immune system and prevent rejection.

Several investigators claim that undifferentiated ES cells are resistant to NK cell attack in vitro and in vivo,17,42,75 whereas others report that stem cells do express NK cell–activating ligands and are susceptible to NK cell attack.40,46 In a study that compared the susceptibility of undifferentiated vs differentiated mouse ES cell–derived cardiomyocytes with NK cell–mediated destruction, undifferentiated ES cells were deemed susceptible to NK cell destruction in a perforin-dependent manner.46 This was attributed to the expression of the NK cell receptor, NK group 2 member D, and the expression of the intercellular adhesion molecule-1. In support of these findings, NK group 2 member D also has been detected in many other mouse pluripotent stem cells.40,43 Interestingly, mouse ES cell–derived cardiomyocytes were not susceptible to NK cell killing, even after stimulation with interferon-γ and retinoic acid, which are known to mediate expression of NK group 2 member D ligands.46 Whether the hypoxic and inflammatory microenvironment of the infarcted heart plays a role in damping the NK cell response remains to be investigated.

**Innate vs Adaptive Immune Responses to Pluripotent Stem Cells Grafts: Insights From Immunodeficient Animal Models**

Pluripotent mouse40,56 and human77,78 stem cells have been studied extensively in immunodeficient recipients. Although the immunobiology of stem cells was not the primary focus, these studies indirectly provided evidence for the absence of specific immune cells in promoting graft survival and, conversely, for their role in clearing teratomas. The pivotal role of T cells in immune rejection of stem cells has been demonstrated using T-cell–deficient mice79,80 and rats.41,81 These studies showed that injection of ES cells is readily followed by teratoma formation. Drukker80 comprehensively investigated immune responses to ES cells using nonobese diabetic/severe combined immunodeficiency (SCID; T- and B-cell–deficient) BALB-nude (T-cell–deficient), C57BL/6-Lystbg (NK cell–deficient), and CBA/CaHN Btkxid (B-cell–deficient) mice. Five weeks after transplantation of ES cells, teratoma formation was detected only in the T-cell–deficient and B-cell–deficient nonobese diabetic/SCID mice. By contrast, transplantation of human ES cells to Lystbg (NK-cell–deficient) and Btkxid (B-cell–deficient) mice led to vigorous rejection and failure to have development teratoma. These experiments demonstrated that xenorejection of human ES cells is T-cell–mediated and that NK or B cells play only a minor role in this process. The role of the complement pathway also has been investigated using an immunodeficient mouse model. Using complement 3–deficient mice, Koch et al82 showed that the homologous complement delays the formation and growth of mouse ES cell–derived teratomas and can completely prevent teratoma formation when a low number of mouse ES cells are implanted (1×10⁵). The authors attributed the susceptibility of ES cells to the complement pathway to low expression of sialic acid. Koch et al82 also investigated the susceptibility of ES cells to B cells and antibodies using J-H- mice (B-cell–deficient). Their results confirmed that B cells and antibodies are not critical for immune rejection of ES cells.

The innate immune response to human ES cells83 and mouse ES cells as well as their derivatives40 also has been studied using immunodeficient mice. Among the cells of the innate immune system, NK cells are the best characterized in the context of stem cell rejection. Mouse ES cell–derived teratomas grew significantly faster in SCID/beige mice (T-, B-, and NK-cell–deficient) compared with SCID (T- and B-cell–deficient).40 NK cell responses to ES cells have been shown to modulate teratoma growth in syngeneic, allogeneic, and xenogeneic immunologic conditions.55 On activation, NK cells have been shown to prevent teratoma formation in 50% of SCID recipients, and teratoma growth, when present, was decelerated.57 Studies in knockout mice null for the recombination-activating gene-2 and cytokine receptor chains that contain the common γ-chain (RAG2γ−/−γ−/−) have implicated NK cells in rejection of HSCs.54 Conversely, ES cell–derived cardiomyocytes46 and vascular progenitor cells57 were not deemed susceptible to NK cell killing. This observation was attributed to the upregulation in MHC-I expression that occurs with differentiation. Conflicting results in susceptibility of NK cell killing described between hematopoietic cells vs pluripotent stem cell–derived cardiomyocytes and endothelial cells suggest that the immune response pathways involved in rejection of the various stem cell derivatives cannot be generalized.

**Rejection of Pluripotent Stem Cells in Different Histocompatibility Settings**

**Xenogeneic**

ES cells transplanted xenogeneically at various anatomic sites (eg, intramuscularly, under the kidney capsule, subcutaneously,
and others) elicit both innate and adaptive immune responses. On intramuscular injection, macrophages, neutrophils, B cells, and CD4+ and CD8+ T cells infiltrate human ES cell grafts.8,38 Rejection of undifferentiated human ES cells has been suggested to be largely T-cell–mediated, whereas NK cells and B cells play only a minor role.37 However, in a rat model, NK cells have been implicated in the killing of undifferentiated mouse ES cells.40 In this study, susceptibility of mouse ES cells to NK killing was attributed to the expression of ligands of the activating NK receptor NK group 2 member D, which was downregulated in differentiated cells. Recently, evidence that implicates the involvement of T cells in the rejection of a clinically relevant cell type was highlighted by Pearl et al.,85 who demonstrated that a regimen consisting of a short-term course of costimulatory blockers that mitigates T-cell alloresponses could extend survival of the human ES cell–derived endothelial cells. However, the effects of these drugs on the innate immune system and how this could have contributed to these findings remain to be examined. In another study, human ES cell–derived cardiomyocytes were injected into immunocompetent rats after myocardial infarction and were shown to survive, proliferate, and integrate with host cardiac tissues.8 In this study, a combination of cyclosporine A and methylprednisolone was used as immunosuppressive therapy and the viability of grafted cells were monitored for up to 8 weeks.

**Allogeneic**

The rejection of allogeneic undifferentiated mouse pluripotent stem cells has been analyzed by several studies, but limited information is available regarding alloresponses to progenies differentiated from these cells. Allogeneic undifferentiated mouse ES cells (2×10^5) injected into ischemic hearts of mice have demonstrated the ability to mobilize innate and adaptive immune responses that resulted in graft destruction 4 weeks posttransplantation.46 The allograft rejection coincided with infiltration of interferon-γ-producing CD3+ T cells and CD11c+ dendritic cells. In a similar study, a higher number of mouse ES cells (1×10^6) was injected into ischemic hearts, and immune cell infiltration was monitored over time at 1, 2, 4, and 8 weeks posttransplantation. A progressive infiltration of CD4+ and CD8+ T cells as well as macrophages, dendritic cells, and granulocytes was observed, predominantly at weeks 4 and 8 after cell implantation.47 Similar results were reported by a different study showing that at 5 weeks after implantation into the myocardium, mouse ES cells were rejected, coinciding with lymphocytic infiltrates.72 The survival of allogeneic mouse ES cells (1×10^6) implanted in the gastrocnemius muscle was also limited to ≈4 weeks as monitored by longitudinal bioluminescence imaging.58 Similar to human endothelial cell progeny, rejection of allogeneic mouse iPS-derived neural progenitor cells has been abrogated by blockers of costimulatory molecules in T cells.85

In an attempt to investigate allogeneic immune responses to human ES cells, Drukker et al.17 used a humanized mouse model termed Trimera. Essentially, Trimera mice are immunodeficient mice reconstituted with human peripheral blood mononuclear cells. Transplantation of undifferentiated human ES cells (1×10^6), differentiated teratoma fragments, or a teratoma-derived primary cell line resulted in tumor formation in all 3 settings. By contrast, Trimera mice were able to completely eliminate Burkitt lymphoma cells. The authors attributed these findings to the hypoimmunogenic nature of human ES cells and their derivative tissues (Figure 4). This hypoimmunogenic phenotype might limit the activation of direct alloreactive T-cell responses. Humanized mouse models represent a very promising platform to study human immune responses in vivo, but results from studies using these models need to be cautiously interpreted because there is evidence that aspects of immune responses in this model may be dysfunctional (eg, defective cytotoxic T cells and NK cells).87,88 As a result of the lack of robust humanized mouse models, the allogeneic immune responses to human ES cells remain poorly characterized. The opportunity to address some of these questions in immunologically healthy humanized animal models will contribute greatly to our understanding of immune responses that thus far have impaired the survival of transplanted pluripotent stem cells in vivo.

**Syngeneic**

Numerous studies have demonstrated that transplantation of mouse ES cells into syngeneic recipients leads to teratoma formation.82,77 However, the characterization of immune responses to syngeneic and clinically relevant ES and iPS cell derivatives is absent or minimal at best. T and B cells as well as macrophages have been shown to infiltrate teratomas in syngeneic mice. Although they were incapable of preventing tumor growth, these lymphocyte infiltrates did decelerate tumor growth.40 Interestingly, teratomas did not develop when a small number of syngeneic ES cells were implanted.40,89,90 Implantation of 5×10^4 undifferentiated or differentiated syngeneic ES cells has been shown to result in teratoma formation in only 33% and 17% of recipients, respectively. However, implantation of high numbers of undifferentiated or differentiated cells (2×10^5) produced teratoma formation in 100% of recipients.40,90 These results suggest that when low numbers of cells are implanted, cells either die immediately after transplantation or are rejected. Implantation of a higher number of cells may overcome immune responses because of intense proliferation or stem cell–mediated immunosuppression (eg, release of transforming growth factor-β and interleukin-10).

One interesting study demonstrated that iPS cells are immunogenic and can be rejected even in MHC-matched recipients.89 CD4+ and CD8+ T cells were implicated in the rejection of syngeneic iPS cell grafts. They attributed their findings to the expression of aberrant genes (ie, Hormad1, Zg16, and Cyp3a11) in iPS cells. They further validated their findings to the expression of aberrant genes in iPS cells, it did not evaluate whether clinically relevant iPS cell therapeutics possess similar immunogenicity. Another caveat was the use of only 1 syngeneic murine ES cell line as control. These omissions make it difficult to assess the significance of their findings and impossible to determine:
(1) whether autogenicity is a property exclusive to iPS cells or also exist in autologous somatic cells maintained in vitro for similar amount of time and in similar culture conditions and (2) whether there are any immunologic benefits of using autologous iPS cells vs allogeneic ES cells. Results from this study are not entirely surprising considering that iPS cells do express several oncofetal antigens, some of which are already known to be immunogenic (eg, octamer-binding transcription factor 4). Some of the dark cloud over iPS cells has recently been lifted with evidence showing that tissues from iPS cell-chimeric mice are not rejected in syngeneic recipients. Nevertheless, it remains unknown whether these results can be extrapolated to stem cell derivatives generated in vitro. The degree of permissible dissimilarities in antigen repertoire between an iPS-derived and an original somatic cell that can guarantee tissue acceptance remains largely unexplored.

**Prospects for Circumventing Immunogenicity**

Evidence obtained from studies that used pluripotent stem cells and their progeny suggests that even full MHC concordance between donor and recipient may not guarantee survival of stem cell therapeutics. Some level of immunosuppression or tolerizing regimen may be required but the extent of immunologic conditioning that will warrant acceptance of stem cell-derived therapeutics remains unknown. In many transplantation scenarios, life-long immunosuppression has been used to accommodate residual antigen disparities between donor and recipient, ensuring the survival of the therapeutic graft. However, this approach can produce devastating toxic side effects, promote opportunistic infections, and increase patients’ susceptibility to malignancies. Because these adverse side effects can outweigh the potential curative benefits of stem cell–derived therapy, strategies to promote long-term tolerance with minimal immunosuppressive therapy are essential.

In a clinical setting, the benchmark for the establishment of tolerance means the complete and successful withdrawal of immunosuppressive drugs. Although tremendous progress has been made in the field of transplantation tolerance during the past half century (Table), durable donor-specific tolerance to prolong transplant survival in humans in the absence of immunosuppressants has not been consistently achieved. Mixed chimerism induced by HSC transplantation is known to promote donor-specific tolerance for >40 years. In mixed chimeric animals, the continued presence of the organ donor’s bone marrow–derived cells in the recipient’s thymus and peripheral lymphoid tissue promotes and maintains immune tolerance by eliminating T-cell clones that react to alloantigens of the graft. However, the use of HSCs to induce tolerance in the clinical setting has been unfeasible thus far, largely because of the unacceptable toxicity, morbidity, and mortality associated with the conditioning needed to achieve engraftment of allogeneic bone marrow, as well as complications such as graft-versus-host disease. Significant efforts have been devoted to developing nonmyeloablative methods for inducing mixed chimerism. Short-term fractionated total lymphoid irradiation (TLI) has

![Figure 4. Mean fluorescence intensity of various human leukocyte antigen (HLA) proteins in several undifferentiated and differentiated human embryonic stem (ES) cell lines.](http://circres.ahajournals.org/)

Reprint from Drukker et al with permission of the publisher. MHC, major histocompatibility complex.
been successfully used to achieve mixed chimerism without graft-versus-host disease in MHC-mismatched mice strains.\textsuperscript{100} TLI radiotherapy is nonmyeloablative and targets major lymphoid organs such as the spleen, thymus, and peripheral lymph nodes. This conditioning has been shown to promote engraftment of bone marrow cells and to promote immunologic tolerance to skin and heart allografts that were transplanted concomitantly with donor bone marrow cells. When combined with antithymocyte serum, TLI also has achieved impressive results in posttransplant conditioning to promote organ allograft tolerance in rats.\textsuperscript{101} In humans, Samuel Strober has tested this regimen at Stanford University for induction of tolerance to kidney transplants. Of 25 kidney transplant recipients conditioned with TLI and antithymocyte globulin, 15 patients had long-term functional grafts with minimal requirement for chronic immunosuppression.\textsuperscript{102}

Some clinically available immunosuppressive regimens have been tested for enhancing the survival of undifferentiated human ES in vivo. Interestingly, the calcineurin inhibitor Tacrolimus, the target of rapamycin inhibitor Sirolimus, and the antiproliferative mycophenolate mofetil have been shown to provide only marginal improvements in the survival of undifferentiated human ES grafts.\textsuperscript{38} By contrast, the target-specific suppression of T cells has been much more effective in this context. The use of minimal host conditioning with nondepleting monoclonal antibodies against CD4 and CD8 was shown to induce long-term acceptance of ES cells–derived embryoid bodies implanted under the kidney capsule.\textsuperscript{19,103} Costimulatory blockade in combination with low-dose total body irradiation (3Gy) has been shown to promote stable mixed chimerism with high levels of engraftment of fully MHC-mismatched HSCs and to enhance tolerance to donor skin grafts.\textsuperscript{104} The costimulatory pathway is mediated by interactions of CD28 and CD40 ligand (also called CD154) on T cells and by B7 (CD80 and CD86) and CD40 on APCs. This pathway is of central importance for T-cell–dependent immune responses, and its manipulation has improved survival of various grafts.\textsuperscript{105,106} Optimal results have been obtained when CD28 and CD40 were blocked simultaneously.\textsuperscript{107,108} A short-course blockade of the costimulatory receptors CD28, CD40 ligand, and lymphocyte-associated antigen-1 on T cells alone has been recently shown to induce long-term acceptance of pluripotent stem cells as well as endothelial and neural progenitors (Figure 6).\textsuperscript{84} Interestingly, this regimen was remarkably more efficient in preventing rejection of pluripotent stem cell grafts than the conventional immunosuppressants Tacrolimus and Sirolimus. Despite these promising results, it is important to note that regimens proved efficient in preventing rejection of undifferentiated ES or iPSC cells will not necessarily work for transplanting differentiated stem cell therapeutics.

Although promising in small animal models, the aforementioned drug regimens have not been able to induce donor-specific tolerance to kidney or to skin allografts in nonhuman primates.\textsuperscript{112,113} Considering the insights gained from various transplantation models in primates, a more holistic approach...
using different immunomodulatory strategies simultaneously (eg, costimulatory blockade, TLI, mixed chimerism, and others) may be better for achieving tolerance with permanent acceptance while reducing or eliminating the need for long-term immunosuppressive therapy. At present, studies focused on immune responses to stem cell therapeutics in primates are still lacking and the immunologic conditioning necessary to guarantee survival of stem cell–derived grafts may prove to be much more modest than expected. Addressing these questions will be critical for the advancement of stem cell technology to clinics.

**Conclusions**

As more diverse pluripotent stem cell derivatives have become available, investigators have learned much about their in vivo behavior, functional properties, and immunogenicity. A comprehensive screening process for antigen repertoire variations among independent stem cell–derived therapeutics will be vital before translation of pluripotent stem cell therapy. Such information, combined with accurate interpretation of data, may facilitate the prediction of immunologic responses and the development of risk scoring for optimal donor–recipient matching. Further understanding of the immunologic pathways triggered by these putative therapeutic cells combined with efficient tracking of immune response is necessary to drive the development of safe strategies to bypass immune rejection. Progress made in these arenas should accelerate the development and clinical application of transiently administered, well-tolerated treatment regimens that exploit the specificity of the immune system while promoting long-term, rejection-free graft survival. Recently, the possibility of cell transdifferentiation, by directly converting or reprogramming a cell type to another while bypassing a pluripotent intermediate, introduces both additional complexity and exciting prospects for regenerative medicine. The investigation into how such an approach compares with pluripotent stem cells in terms of therapeutic repertoire of cell types, and whether transdifferentiated cells are functional or nonimmunogenic in the host, will be a new frontier in this fast-paced field.

**Acknowledgments**

The authors thank Amy Morris for preparing the illustrations and Dr Everett Meyer for valuable advice and constructive critical input. As a result of space constraints, the authors were unable to include all relevant and important studies regarding the immunologic barriers to pluripotent stem cell therapy. The authors apologize to those investigators whose valuable work has been omitted in this review.

**Sources of Funding**

This work was supported, in part, by National Institutes of Health AG036142, AI085575, HL099117, GM099130, and EB009689 J.C.Wu, and the International Society for Heart and Lung Transplantation P.E. de Almeida.

**Disclosures**

None.

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Circ Res. 2013;112:549-561
doi: 10.1161/CIRCRESAHA.111.249243

Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7330. Online ISSN: 1524-4571

The online version of this article, along with updated information and services, is located on the World Wide Web at:
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