Mesenchymal stem cells as a vector for the inflammatory prostate microenvironment

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Abstract

Mesenchymal stem cells (MSCs) have an inherent tropism for sites of inflammation, which are frequently present in sites of cancer, including prostatic lesions. MSCs have been defined as CD73/CD90/CD105 triple-positive cells in the absence of hematopoietic lineage markers with the ability to differentiate into multiple mesodermal lineages, including osteoblasts, adipocytes, and chondrocytes. Our group has previously demonstrated that MSCs represent between 0.01 and 1.1% of the total cells present in human prostatectomy tissue. In addition to their multi-lineage differentiation potential, MSCs are immunoprivileged in nature and have a range of immunomodulatory effects on both the innate and adaptive arms of the immune system. MSCs have been detected in an increasing array of tissues, and evidence suggests that they are likely present in perivascular niches throughout the body. These observations suggest that MSCs represent critical mediators of the overall immune response during physiological homeostasis and likely contribute to pathophysiological conditions as well. Chronic inflammation has been suggested as an initiating event and progression factor in prostate carcinogenesis, a process in which the immunosuppressive properties of MSCs may play a role. MSCs have also been shown to influence malignant progression through a variety of other mechanisms, including effects on tumor proliferation, angiogenesis, survival, and metastasis. Additionally, human bone marrow-derived MSCs have been shown to traffic to human prostate cancer xenografts in immunocompromised murine hosts. The trafficking properties and immunoprivileged status of MSCs suggest that they can be exploited as an allogeneic cell-based vector to deliver cytotoxic or diagnostic agents for therapy.

Key Words

- mesenchymal stem cell
- MSC
- inflammation
- prostate cancer
- multipotent stromal cell

Introduction

The prostate is the most common organ in the human body to undergo neoplastic transformation when accounting for both benign and malignant lesions. Pathological benign prostatic hyperplasia (BPH) affects >50% of men over the age of 50 years with nonclinical incidence representing a far greater number (Berry et al. 1984). Similarly, autopsy studies have demonstrated histological prostate cancer in as many as 50% of men by the age of 50 years with a linear increase in incidence for each subsequent decade of life (Delongchamps et al. 2006). The etiology of BPH and prostate cancer is unclear; however, chronic inflammation has been suggested as a
contribute to altered antigen processing and epithelial cells and glandular structure as a result of these factors. Though inflammation is commonly present, external pathogens often cannot be identified within these lesions (De Nunzio et al., 2011), suggesting that the inflammatory response persists after the pathogen is cleared or non-pathogenic stimuli are responsible. Other causative agents of prostatic inflammation include dietary and hormonal factors, in addition to chemical and physical irritations resulting from urine reflux and corpora amylacea respectively (De Marzo et al., 2007, De Nunzio et al., 2011). Furthermore, damage to epithelial cells and glandular structure as a result of these factors can contribute to altered antigen processing and presentation, which can generate an autoimmune response if these peptides are not recognized as ‘self’ or tolerance is broken (De Nunzio et al., 2011, Jackson et al., 2012). Independent of the origin, a chronic inflammatory state can arise as made evident by an age-associated persistent presence of an infiltrating leukocyte population (Kramer et al., 2007, Nickel et al., 2008).

A heuristic model of prostate carcinogenesis suggests that prostate cancer progresses through proliferative inflammatory atrophy (PIA) and prostatic intraepithelial neoplasia (PIN) precursor lesions prior to malignant transformation (Fig. 1). PIA is defined as focal sites of hyperplastic epithelial atrophy that are frequently associated with inflammation (De Marzo et al., 1999, Nelson et al., 2003). PIA is often adjacent to areas of PIN, which are characterized by intraductal cellular proliferation with no evidence of basement membrane and stromal invasion (Clouston & Bolton, 2012). During both normal physiological processes and pathophysiological states, dynamic interactions initiated by paracrine mediators occur between the epithelium and cells normally restricted to the stroma, including smooth muscle cells, fibroblasts, bone marrow-derived mesenchymal stem cells (BM-MSCs), and various inflammatory cells. The latter of these have not only been associated with the initiation of prostate cancer but have also been suggested as potential drivers of its progression by virtue of DNA-damaging reactive oxygen species, a variety of immunosuppressive mechanisms, and the secretion of mitogenic and pro-angiogenic cytokines (Nelson et al., 2003, De Marzo et al., 2007, Sfanos & De Marzo, 2012). Once the cancer cells have penetrated the basement membrane, they have direct contact with cells that were previously restricted to paracrine interactions, in addition to direct access to growth factors, survival signals, pro-invasion molecules, and extracellular matrix proteins. In total, these are collectively known as the tumor microenvironment and can have profound effects on cancer progression, malignancy, and therapeutic outcome (Cunha et al., 2003, Bissell & Hines, 2011, Dayyani et al., 2011, Hanahan & Weinberg, 2011, Brennen et al., 2012, Correia & Bissell, 2012).

Chemokines, such as CXCL12 (SDF-1), CCL5 (RANTES), and CCL2 (MCP-1) and the rest of the inflammation-associated secretory milieu, have been shown to recruit MSCs to these sites as a result of the high expression of chemokine and cytokine receptors on their surface (Spaeth et al., 2008). Recently, our group has demonstrated that MSCs are not only present at sites of human prostate cancer but also represent 0.01–1.1% of the total cells present in human prostatectomy tissue cores (Brennen et al., 2013). MSCs have been shown to be critical mediators of the overall immune response (Caplan, 2009, Newman et al., 2009, English & Mahon, 2011) and, therefore, may contribute to carcinogenesis through a variety of mechanisms, including stimulation of proliferation, angiogenesis, and metastasis, in addition to their immunosuppressive properties (Bergfeld & DeClerck, 2010, Klopp et al., 2011). These latter properties may be particularly relevant in tumor progression as the cancer cells must escape immune surveillance and clearance to reach their full malignant potential (Fig. 1). Perhaps more importantly, the tumor trafficking properties of MSCs suggest that they could be used to deliver therapeutic or diagnostic agents to sites of prostate cancer, both primary and secondary lesions (Brennen et al., 2013).

**MSCs: mesenchymal stem cells**

Recently, there has been an increasing appreciation for the role of MSCs, also known as multipotent stromal cells, in modulating both innate and adaptive immune responses. These cells were initially characterized by Friedenstein et al. (1970) as clonogenic cells in culture that were multipotent stromal precursors. Throughout much of the early literature, these cells were referred to as colony-forming unit fibroblasts or CPU-Fs (Friedenstein et al., 1976), until Caplan proposed the term ‘Mesenchymal Stem Cells’ in 1991 (Caplan, 1991). Over the ensuing years, there has been much debate regarding the appropriateness of this terminology (Horwitz et al., 2005, Bianco et al., 2008, ...
Ho et al. 2008, Nombela-Arrieta et al. 2011); however, this continues to be the accepted consensus in the literature.

The International Society for Cell Therapy has minimally defined MSCs as plastic-adhering multipotent cells of fibroblastoid morphology with the ability to differentiate into cells of the osteogenic, adipogenic, and chondrogenic lineages (Pittenger et al. 1999, Dominici et al. 2006). MSCs have been further defined based upon the expression of CD90 (Thy-1), CD105 (endoglin), and CD73 (5′-nucleotidase) in the absence of hematopoietic lineage markers, including CD45, CD34, CD14 or CD11b, CD79a or CD19, and HLA-DR expression (Dominici et al. 2006). Although some are more controversial than others, there is also evidence to suggest that MSCs can differentiate into myocytes (Wakitani et al. 1995, Crisan et al. 2008), fibroblasts (Lee et al. 2010), pericytes (Hirschi & D’Amore 1996, Crisan et al. 2008), and neurons (Woodbury et al. 2000, Hofstetter et al. 2002, Bertani et al. 2005, Krampera et al. 2007, Phinney & Prockop 2007), although neuronal differentiation appears to be correlated with the age of the donor (Hermann et al. 2010, Brohlin et al. 2012). The number of MSCs in an individual declines with age, as demonstrated by a 100-fold decrease in the ability of nucleated marrow cells to form colonies (CFU-F), from \(10^4\) in newborns to \(10^6\) in the elderly (Caplan 2009). Furthermore, while MSCs are generally thought to be derived from the mesoderm (Vodyanik et al. 2010), there is an initial wave of neuroectodermal MSCs during embryogenesis that arise from the neural crest (Takashima et al. 2007, Morikawa et al. 2009). Additional evidence suggests that the percentage of MSCs derived from the neural crest declines with age (Takashima et al. 2007), which may explain the loss of neuronal differentiation potential observed in MSCs derived from older donors. Additionally, the mesenchymoangioblast was also recently identified as a

Figure 1
MSCs in the normal and malignant prostate. A heuristic model of prostate carcinogenesis suggests that the normal gland progresses through proliferative inflammatory atrophy (PIA) and prostatic intraepithelial neoplasia (PIN) stages on its path to malignant transformation. MSCs likely have significant immunomodulatory roles not only in the normal prostate but throughout all stages of prostate cancer tumorigenesis and progression as well. These properties are mediated through the secretion of various chemokines (SDF1, CCL2, and CCL5), cytokines (IL4, IL6, IL8, IL10, M-CSF, IFN-\(\gamma\), and TNF-\(\alpha\)) and other bioactive signaling molecules (TGF-\(\beta\), PG, and IDO) that can indirectly affect carcinogenesis through leukocyte intermediates but also through direct effects on the cancer cells themselves. A full colour version of this figure is available via http://dx.doi.org/10.1530/ERC-13-0151.
mesoderm-derived precursor able to generate both MSCs and endothelial cells (Vodyanik et al. 2010). MSCs have also been isolated from numerous peripheral tissues, including fat, skin, dental pulp, and pancreas (Zuk et al. 2002, da Silva Meirelles et al. 2006, Zhang et al. 2006, Davani et al. 2007, Crisan et al. 2008, Blasi et al. 2011) and are likely present in all tissues at low levels as part of a homeostatic surveillance mechanism.

**MSCs: tissue of origin**

MSCs isolated from these peripheral tissues are frequently thought of as equivalent to those derived from bone marrow due to significantly overlapping properties; however, there is accumulating evidence to suggest that there are differences between these populations, including their expression profiles (Panepucci et al. 2004, Wagner et al. 2005, Park et al. 2007, Noel et al. 2008, Jansen et al. 2010, Strioga et al. 2012) and differentiation potential (Sakaguchi et al. 2005, Musina et al. 2006, Strioga et al. 2012). These differences may reflect a ‘memory’, epigenetic or otherwise, associated with distinct signaling events and cellular interactions that occur between MSCs and unique microenvironments. For example, multiple studies have shown that MSCs isolated from fat tissue, or adipose-derived stem cells (ADSCs), have an increased propensity to form adipocytes relative to those derived from bone marrow (Sakaguchi et al. 2005, Musina et al. 2006). Both synovium- and BM-MSCs seem to have a greater ability to generate chondrocytes than ADSCs (Sakaguchi et al. 2005, Afizah et al. 2007). Additionally, ADSCs generate osteoblasts with less efficiency relative to their bone marrow-derived counterparts (Sakaguchi et al. 2005). However, other studies have shown that both BM-MSCs and ADSCs have equal osteoblast and adipocyte differentiation potential (De Ugarte et al. 2003, Krampera et al. 2007, Noel et al. 2008, Pachon-Pena et al. 2011). Our own studies suggest that MSCs from the prostates of young, healthy men selectively lose their adipocyte differentiation ability (W N Brennen, S Chen and J T Isaacs 2013, unpublished observations), while those isolated from cancerous prostates in older men retain their tri-lineage differentiation potential (Brennen et al. 2013), which may reflect their more recent exodus from the bone marrow and represent a more naïve commitment status.

Importantly, inter-individual variation in the proliferative capacity and differentiation potential of donor-derived MSCs can make the interpretation of such comparisons difficult, which can be further compounded by differences in optimal culture conditions that are yet to be fully standardized for MSCs obtained from alternative tissue sources (Huang et al. 2005, Sakaguchi et al. 2005, Wagner et al. 2005, Ho et al. 2008, Pevsner-Fischer et al. 2011, Rada et al. 2011, Brennen et al. 2013). This variability can be alleviated, in part, by comparing a panel of tissue-specific MSCs isolated from a single individual. Indeed, such studies appear to confirm observations suggesting a restricted differentiation potential related to a tissue-of-origin ‘memory’ (Sakaguchi et al. 2005, Afizah et al. 2007). For instance, BM-MSCs have greater chondrogenic potential than ADSCs isolated from the same patient (Huang et al. 2005, Afizah et al. 2007). Sakaguchi et al. (2005) also demonstrated distinct differences in the differentiation efficiencies of patient-matched MSCs isolated from multiple tissues and expanded under similar conditions. Furthermore, gene expression and proteomic analyses of MSCs from different sources have also demonstrated distinct profiles despite significant similarities (Wagner et al. 2005, Noel et al. 2008, Jansen et al. 2010). For example, increased expression of osteogenesis- and angiogenesis-associated genes was measured in BM-MSCs and umbilical cord MSCs relative to each other respectively (Panepucci et al. 2004). Minimally, these observations highlight the heterogeneity of isolated MSC populations with regard to their differentiation potential, embryonic lineage, tissue source, and donor age.

**MSCs in the clinic**

Numerous clinical trials over the last decade were designed to exploit the multipotent differentiation potential of MSCs for a range of pathological conditions, including myocardial infarction (MI), spinal cord injury, and osteogenesis imperfecta. While promising results were obtained in early phase clinical trials, the high hopes for these MSC-based regenerative strategies were largely unrealized in the accompanying phase III trials. Follow-up on these studies suggested a lack of long-term tissue engraftment (<1%) with no evidence of differentiation into the anticipated cell types following systemic administration (Ankrum & Karp 2010). In contrast to the results from in vitro differentiation assays, these clinical observations questioned the assumption that MSC’s primary role in tissue repair is to reconstitute damaged cell types. However, despite the lack of differentiation, there were positive therapeutic effects observed in select patients from these trials. Concurrent laboratory investigations led to an emerging realization that MSCs function through trophic and immunomodulatory mechanisms based on the secretion of bioactive molecules...
MSCs have been shown to secrete numerous growth factors, cytokines, and chemokines, in addition to pro-angiogenic, anti-apoptotic, and anti-inflammatory signals, including transforming growth factor β (TGF-β), granulocyte-macrophage colony-stimulating factor (GM-CSF), interleukin 6 (IL6), regulated on activation, normal T cell expressed and secreted (RANTES), CCL2, vascular endothelial growth factor (VEGF), hepatocyte growth factor (HGF), prostaglandins (PGs), and IL10, to name a few (Newman et al. 2009, Zhukareva et al. 2010, English & Mahon 2011). Although some groups only detect IL10 in MSC-leukocyte co-cultures (Tse et al. 2003, Beyth et al. 2005, Rasmusson et al. 2005), others have reported the constitutive expression of IL10 by MSCs in monoculture as well (Aggarwal & Pittenger 2005, Barry et al. 2005, Coffelt et al. 2009, Mougiakakos et al. 2011, Technau et al. 2011). Additionally, molecular profiling has revealed that MSCs express a large repertoire of cytokine and chemokine receptors that are believed to mediate their trafficking to inflammatory sites (Spaeth et al. 2008). The paracrine effects of these secreted molecules likely explain the observed clinical benefits seen thus far and have formed the underlying rationale for the majority of current MSC-based clinical trials designed to treat various inflammatory and autoimmune disorders.

To date, a number of clinical trials have been completed in which ex vivo expanded MSCs have been administered for applications as diverse as enhancing cardiac function post-MI, promoting hematopoietic stem cell engraftment, mitigating graft-vs-host-disease (GVHD), and treating a host of autoimmune disorders (Lazarus et al. 2005, Le Blanc et al. 2008, Hare et al. 2009, Garcia-Gomez et al. 2010). The most commonly studied application of systemic allogeneic MSCs has been as a means to decrease or prevent GVHD. Two phase III trials enrolling a total of 452 patients have evaluated the efficacy of allogeneic MSCs in patients with GVHD have been completed. While neither trial met its primary endpoint of complete response, there were some clinical benefits observed in those with steroid-refractory GVHD. These results ultimately lead to the approval in Canada of Prochymal, a pre-manufactured, universal donor MSC product, in acute pediatric GVHD (Prasad et al. 2011, Osiris Therapeutics 2012). More importantly, as was true with earlier phase studies, no adverse events were noted after infusion of MSCs in any patient being treated on either GVHD protocol. A variety of phase I/II studies testing the effect of MSCs in the setting of MI, chronic obstructive pulmonary disease, liver cirrhosis, lupus, and type II diabetes have also been reported (Hare et al. 2009, Jiang et al. 2011, Zhang et al. 2012, Li et al. 2013, Weiss et al. 2013). Thus far, no significant MSC-related adverse events have been reported across these various phase I/II studies (Lalu et al. 2012). Currently, a number of additional randomized trials are underway utilizing MSCs in a range of different diseases (Garcia-Gomez et al. 2010). In summary, the combined results from a large number of trials indicate that i.v. administration of unmodified human BM-MSCs, whether autologous or allogeneic, can be safely administered to patients without producing significant side effects.

**MSCs: firemen of the immune system**

MSCs are generally thought to be non-immunogenic due to their lack of both MHC-II expression and the associated co-stimulatory molecules (Tse et al. 2003). Importantly, MSCs do express low levels of MHC-I, which prevents them from being recognized and lysed by NK cells (Newman et al. 2009). Furthermore, the constitutive expression of factor H makes MSCs resistant to complement-mediated lysis (Tu et al. 2010). Secretion of factor H extends this protection to other cells in the local microenvironment and represents one of many mechanisms through which MSCs suppress both the innate and adaptive immune responses (Fig. 2). MSCs inhibit the proliferation and activation of NK cells through expression of PGs and indoleamine dioxygenase (IDO; English & Mahon 2011). MSCs secreted PGs have also been shown to suppress mast cell degranulation, trafficking, and tumor necrosis factor α (TNFα) expression (Brown et al. 2011), in addition to promoting macrophage M2 polarization (Prockop 2013). Secretion of TSG-6 by MSCs has multiple anti-inflammatory properties, including inhibition of TLR2-induced NF-κB signaling in macrophages by blocking CD44 stimulation, abrogation of neutrophil migration, and suppression of pro-inflammatory protease activity (Lee et al. 2009, Prockop & Oh 2012, Prockop 2013). Additionally, MSCs block the secretion of pro-inflammatory cytokines from activated macrophages, prevent the oxidative burst associated with neutrophil function, and suppress eosinophil trafficking to inflammatory tissues (Newman et al. 2009, English & Mahon 2011). MSC-derived IL6 inhibits dendritic cell (DC) maturation from monocytes, in addition to suppressing the expression of MHC-II and the CD40 and CD86 co-stimulatory molecules required for T-cell activation (Djouad et al. 2007). By blocking DC maturation and antigen presentation, MSCs induce a tolerogenic phenotype in which DCs downregulate the expression of
The Innate Immune System

- NK Cell: Proliferation, Cytotoxicity, IFN-γ
- Mast Cell: Degranulation, TNFα, Trafficking
- Dendritic Cell: DC Maturation, TNFα, Tolerogenic DC, IL-10
- Neutrophil: Trafficking, Apoptosis, ROS
- Complement System: MAC-mediated lysis
- Eosinophil: Trafficking

The Adaptive Immune System

- Treg: Proliferation, Activation, IFN-γ, TNFα, Cytotoxicity
- Effector T Cell (CD4+): Proliferation, IFN-γ, IL-4, Polarization (Th1, Th2, Th17)
- Effector T-cell (CD8+): Proliferation, Cytotoxicity

Figure 2

Immunosuppressive properties of MSCs on both the innate and adaptive arms of the immune system. MSC trafficking from the bone marrow in response to an inflammatory stimulus, in addition to MSCs, already present in the local microenvironment can profoundly affect the overall immune response. The immunosuppressive effects of MSCs are mediated through both direct cell contact in some cases, and the secretion of numerous paracrine signals that effect proliferation, survival, trafficking, maturation, polarization, activation, cytotoxicity, and the secretion of additional inflammatory mediators. These effects occur between MSCs and nearly all components of both the innate and adaptive immune system, which suggests that MSCs may represent a central hub in the regulatory networks of the immune system. A full colour version of this figure is available via http://dx.doi.org/10.1530/ERC-13-0151.
pro-inflammatory cytokines, such as TNFα, while upregulating the expression of IL10 and other anti-inflammatory cytokines (Aggarwal & Pittenger 2005).

Inhibition of MHC-II-mediated antigen presentation by DCs prevents T-cell activation and proliferation. Furthermore, MSCs promote the generation of regulatory T cells; suppress Th1, Th2, and Th17 polarization; and inhibit the proliferation and activation of cytotoxic T cells (CTLs); thereby, shifting the T-cell response to an immunosuppressive state (Newman et al. 2009, English & Mahon 2011). Multiple studies have also demonstrated that MSCs inhibit B-cell activation, proliferation, migration, and immunoglobulin expression (Corcione et al. 2006, Newman et al. 2009). These effects are mediated by both soluble factors and direct cell–cell contact; the latter of which activates programmed death pathway-1 (PD-1) signaling and is at least partially responsible for the attenuation of B-cell proliferation and altered cytokine receptor expression in mice (Augello et al. 2005). These observations suggest that a primary physiological function of MSCs is to promote an immunosuppressive microenvironment (Fig. 2). This MSC-mediated immunosuppression likely represents a critical negative feedback mechanism to prevent unchecked chronic inflammation. Together with other regulatory mechanisms, this negative feedback helps to prevent an uncontrolled self-reinforcing ‘cytokine storm’, or hypercytokinemia, that can lead to increased vascular permeability, tissue edema, autoimmune disorders, fibrosis, acute respiratory distress syndrome, organ failure, cancer, or even death in extreme cases (Osterholm 2005, La Gruta et al. 2007).

MSCs: immunoprivileged or not?

While MSCs are traditionally thought to be non-immunogenic and immunosuppressive due to the properties described above, some recent studies have suggested that MSCs may be immunogenic under certain conditions (Eliopoulos et al. 2005, Nauta et al. 2006, Huang et al. 2010). The rejection of allogeneic MSCs in immunocompetent MHC mismatched mice was associated with an increase in infiltrating CTLs, natural killer T cells, and NK cells (Huang et al. 2010). Additionally, while syngeneic murine MSCs were associated with tolerance to both donor and recipient antigens in an allogeneic bone marrow transplant model, the same study also demonstrated that transplantation of MHC-matched MSCs and BM into an allogeneic recipient decreased engraftment efficiency (Nauta et al. 2006). In contrast, no effect on BM engraftment was observed when MSCs from a third-party donor were used. Furthermore, while allogeneic MSCs only triggered rejection when they were MHC-matched to the BM donor, both third-party and BM-matched MSCs were able to induce a memory T-cell response, which strongly suggests that allogeneic murine MSCs are immunogenic (Nauta et al. 2006). Unlike human MSCs, which only express MHC-II following stimulation with interferon (IFN)-γ, the murine MSCs used in these studies express low levels of MHC-II under non-stimulated conditions (Eliopoulos et al. 2005). Unsurprisingly, this basal expression of MHC-II renders murine MSCs immunogenic in an allogeneic setting and likely explains the results observed in these studies.

Like humans and other higher order mammals, rat MSCs, in contrast to their murine cousins, do not express MHC-II antigens under basal conditions (Newman et al. 2009); however, induction of MHC-II expression was detected following myogenic, endothelial, and smooth muscle differentiation (Huang et al. 2010). Furthermore, these differentiated MSCs were cleared from recipient tissues and donor-specific alloantibodies were detected in the serum of recipient rats at 5 weeks post-injection. Similarly, expression of HLA-DR, a MHC-II antigen, is induced following chondrogenic differentiation of adipose-derived human MSCs (ADSCs) in vitro (Technau et al. 2011). Interestingly, these chondrocyte-differentiated ADSCs continued to express the immunosuppressive HLA-G antigen and secrete IL10, suggesting that they may retain their immunosuppressive properties post-differentiation. Increased immunogenicity following differentiation would potentially explain the lack of data demonstrating long-term engraftment in patients following allogeneic MSC infusion. Indeed, Niemeyer et al. (2008) found no evidence of BM-MSCs that were osteogenically induced ex vivo prior to infusion in recipient animals; by contrast, undifferentiated BM-MSCs were detected in all recipients following xenotransplantation. Additionally, both allogeneic and autologous BM-MSCs are susceptible to complement-mediated lysis in the presence of serum following ex vivo culturing, despite the expression of factor H and other negative regulators (Li & Lin 2012).

Other studies have demonstrated that neither differentiated nor undifferentiated allogeneic MSCs induce a proliferative response in mixed lymphocyte cultures (Le Blanc et al. 2003a) or in a rabbit model of osteogenesis (Liu et al. 2006). Additionally, early studies failed to detect alloantibodies against MSCs in the serum of patients receiving therapeutic doses of allogeneic MSCs (Le Blanc et al. 2003a).
et al. 2004, Sundin et al. 2007), suggesting that the immunoprivileged phenotype of MSCs remains dominant even if they do undergo differentiation in vivo. However, recent studies have reported the presence of anti-donor antibodies in the serum of a minority of patients. Weak alloimmune reactions were detected in 3.7% of patients in the POSEIDON randomized trial comparing allogeneic to autologous BM-MSC therapy for ischemic cardiomyopathy (Hare et al. 2012). In a press release reporting the results from Mesoblast’s phase 2 trial evaluating MSCs in patients with cardiovascular disease, anti-donor antibodies were detected in 13% of patients (PRNewswire 2011). Importantly, no adverse clinical effects were associated with the presence of alloantibodies in either of these studies.

Ex vivo culturing conditions, particularly with respect to FBS, have been shown to affect the immunogenicity of MSCs and may explain some of the mixed results observed between laboratories (Sundin et al. 2007, Newman et al. 2009). Multiple trials evaluating the use of autologous MSCs for a variety of conditions have recently been completed or are in progress, and reports on their engraftment efficiency compared with their allogeneic counterparts will address this possibility in a more definitive manner. Importantly, there have been no adverse clinical events, immunological or otherwise, associated with either systemic or local administration of MSCs in the thousands of patients that have been accrued in these trials (Ankrom & Karp 2010, Lalu et al. 2012), which emphasizes the overall safety of MSC-based therapeutic strategies. The spontaneous malignant transformation of human MSCs during prolonged expansion ex vivo has also been raised as a potential safety concern regarding their clinical use; however, reports on this phenomenon were later corrected or retracted by admissions of contamination in the MSC cultures with other cancer cell lines (Garcia et al. 2010, Torsvik et al. 2010, Vogel 2010, Klopp et al. 2011). Of note, patients enrolled in MSC-based clinical trials often receive multiple doses of >10^8 cells, and no transformation of MSCs in these patients have been reported to date. A recent autopsy study of 18 patients receiving infusions of HLA-mismatched MSCs found no evidence of ectopic tissue formation or malignant tumors derived from donor MSCs (von Bahr et al. 2012). Furthermore, in eight patients with tissue samples collected more than 50 days post-infusion, low levels of MSC donor DNA (<1/1000) were only detected in the lung and kidney of a single patient each. These data corroborate previous clinical observations, suggesting that MSCs have limited long-term engraftment capabilities, which serves to highlight the overall lack of tumorigenic potential for these cells in an allogeneic therapeutic setting.

MSCs: complexities and immunostimulatory properties

There is accumulating evidence to suggest that the interactions between MSCs and immunological effector cells are more complex than those previously appreciated (Fig. 3). For example, MSCs are known to inhibit the IL2-stimulated proliferation of resting NK cells; however, activated NK cells are not only more resistant to MSC-mediated proliferative suppression but have also been shown to lyse both autologous and allogeneic MSCs in the absence of IFN-γ (Spaggiari et al. 2006). This lysis occurs as a result of the expression of NK-activating ligands by MSCs (Spaggiari et al. 2006). Binding of these ligands to their cognate receptors on the surface of NK cells triggers their recognition and destruction by NK cells, despite the low levels of MHC-I expression on MSCs. Exposure to IFN-γ in an inflammatory microenvironment significantly upregulates MHC-I expression on MSCs and protects them from NK-mediated lysis (Eliopoulos et al. 2005, Spaggiari et al. 2006). Additionally, IFN-γ-stimulated MSCs also express MHC-II and can function as antigen-presenting cells (APCs; Chan et al. 2006, Stagg et al. 2006). Interestingly, these antigen-presenting properties are biphasic and only present during a narrow range of IFN-γ concentrations with high levels leading to a decrease in APC functions (Chan et al. 2006). MSCs also possess direct antimicrobial activity mediated through the secretion of cathelicidin hCAP-18/LL-37, a peptide with activity against both Gram-positive and -negative bacteria (Krasnodembskaya et al. 2010).

The differential activation of TLR signaling in MSCs has also been shown to be a critical mediator of their immunomodulatory properties (Pevsner-Fischer et al. 2007, Liotta et al. 2008). TLR-2 stimulation suppresses MSC differentiation, while promoting their proliferation and immunosuppressive phenotype (Pevsner-Fischer et al. 2007). By contrast, TLR-3 and -4 signaling inhibits this immunosuppressive activity without affecting their differentiation potential (Liotta et al. 2008). Activation of different TLR signaling pathways in response to various pathogen-associated molecular patterns (PAMPs) has also been proposed to explain the ability of MSCs to promote tissue repair and control the inflammatory reaction without negatively impacting the ability of the immune system to fight off invading pathogens (English & Mahon...
2011). These observations suggest a model where MSCs would function in a dichotomous manner depending on the nature of the infectious insult and the extent of the immunological response. MSCs would initially behave as APCs to activate an adaptive response following PAMP recognition and IFN-γ stimulation, and the immunosuppressive effects would take dominance during prolonged inflammation with increasing IFN-γ levels (Fig. 3). In further support of this model, the effect of MSCs on lymphocyte proliferation seems to be dependent on the MSC-to-lymphocyte ratio present. Low ratios of MSCs to lymphocytes, as would be seen in the initial phases of inflammation, stimulated lymphocyte proliferation through soluble paracrine mediators, whereas, higher ratios, which may occur after a prolonged inflammatory response, resulted in inhibition of lymphocyte proliferation (Bocelli-Tyndall et al. 2009). Evolutionarily, this negative feedback mechanism would serve to limit the immune response and prevent an unbridled leukocytic infiltrate from initiating a self-reinforcing loop of chronic inflammation, which could potentially lead to associated pathological conditions. This parallels a recent model proposed by English & Mahon (2011) in which they describe MSCs as a sort of inflammatory rheostat or ‘licensing switch’ to modulate the immune response. Additional support for the role of IFN-γ in regulating the immunomodulatory properties of MSCs comes from observations demonstrating that MSC-mediated suppression of T-cell proliferation is enhanced by IFN-γ secreted by activated NK and T cells (Krampera et al. 2006, English et al. 2007). Furthermore, in contrast to wild-type MSCs, IFN-γ receptor 1-null MSCs were unable to prevent GVHD in mice, suggesting that inflammation and IFN-γ signaling in particular are required for the immunosuppressive effects of MSCs (Ren et al. 2008b). Importantly, these immunomodulatory properties are probably not dictated by IFN-γ alone but are the result of a complex interplay between IFN-γ, TNFz, and the entire panoply of inflammatory cytokines, chemokines, and signaling molecules present within the local microenvironment.

MSCs and the inflammatory prostate

A model in which MSCs play a primary role in modulating the immune response implies that these cells are present in, or continuously fluxing through, all tissues. Accumulating evidence supports this model. In addition to the bone marrow, MSCs have been isolated from a growing list of tissues, including adipose tissue, skin, muscle, dental pulp, pancreas, intestine, lung, and peripheral blood (Zuk et al. 2002, Kassis et al. 2006, Zhang et al. 2006, Davani et al. 2007, Lama et al. 2007, Crisan et al. 2008, Lanzoni et al. 2009, Blasi et al. 2011), with all available evidence suggesting that they reside in perivascular niches within all tissues (da Silva Meirelles et al. 2006, Crisan et al. 2008). While this is a rare, but detectable, population of cells within these tissues under homeostatic conditions, there is a dramatic influx from the bone marrow in response to an inflammatory insult (Spaeth et al. 2008, Newman et al. 2009). It is well known that the prostate is bombarded with inflammatory and infectious agents throughout an individual’s lifetime, with as many as 80% of men showing evidence of a leukocytic infiltrate in their prostate when biopsied (De Marzo et al. 2007, Nickel et al. 2008, Sfanos & De Marzo 2012). Additionally, the formation of corpora amylacea, which are aggregates of inflammatory proteins, is thought to begin early in life and increase with age, becoming highly prevalent within the prostates of older men (Sfanos & De Marzo 2012). The presence of prostatic inflammation, or prostatitis, likely extends to all men at some point in their lives as many inflammatory stimuli will be resolved without generating overt clinical symptoms.

Therefore, it is unsurprising that MSCs can also be isolated from the prostates of both young and old men (Brennen et al. 2013, S Chen, W N Brennen and J T Isaacs 2013, unpublished observations). Lin et al. (2007) isolated cells consistent with an MSC phenotype from BPH tissue, a disease characterized by a hyper-proliferative stroma. Despite their ability to differentiate into the myogenic, adipogenic, and osteogenic lineages, the authors concluded that these cells did not represent MSCs due to their inability to generate neural cells, a property later shown to decrease with age (Hermann et al. 2010, Brohlin et al. 2012), thereby explaining the lack of this particular differentiation potential in BPH cells isolated from older men. Additionally, MSCs incorporate into the re-growing prostates of castrated mice following testosterone supplementation (Placencio et al. 2010). In addition to older men with prostate cancer, our own laboratory has cultivated MSCs (CD90+/FAP+/CD105+/CD73+/HLA-DR−) from the prostate of a 20-year-old healthy organ donor (S Chen, W N Brennen and J T Isaacs 2013, unpublished observations), suggesting that MSCs are present in the prostate throughout an individual’s lifetime to varying degrees.

Chronic inflammation is thought to be an initiating event for prostatic carcinogenesis (Nelson et al. 2003, De Marzo et al. 2007). Numerous factors have been implicated in the initiation of an inflammatory microenvironment within the prostate, including diet, infectious agents, physical trauma induced by corpora amylacea, hormonal
changes, and urine reflux (Sfanos & De Marzo 2012). Independent of the cause, the resulting inflammatory signals act as a chemoattractant for circulating BM-MSCs (Fig. 1) due to the extensive array of chemokine and cytokine receptors expressed on their cell surface (Spaeth et al. 2008). CXCL12 (SDF-1), CCL5 (RANTES), and CCL2 (MCP-1), in particular, have been shown to be highly overexpressed in prostate cancer (Sun et al. 2003, Vaday et al. 2006, Fujita et al. 2010), all of which have also been implicated in MSC trafficking to inflammatory sites (Spaeth et al. 2008). Multipotent MSCs of mouse origin have been isolated from prostate cancer xenografts using a side population assay (Santamaria-Martinez et al. 2009). Additional evidence consistent with the presence of MSCs in human prostate cancer includes the characteristic over-expression of CD90 (True et al. 2010), a marker of not only MSCs but also endothelial cells, hematopoietic precursors, neurons, thymocytes, and NK cells. Interestingly, in a series of prostate cancer tissue samples with high CD90 expression, these same authors showed a non-comparable increase in CD45-positive cells, suggesting that the increased CD90 expression was not merely due to excessive leukocyte infiltration (Liu et al. 2004). Importantly, not all these extra CD90-positive cells are likely to represent bona fide MSCs as this population also includes MSCs at various stages of differentiation, endothelial cells, hematopoietic progenitors, and carcinoma-associated fibroblasts (CAF). Furthermore, while CD90 expression is significantly elevated in malignant prostatic lesions, rare CD90+ cells can also be detected in normal prostate tissue (Zhao & Peehl 2009, True et al. 2010), which is consistent with the presence of a small population of MSCs in all tissues. CD90-positive cells have also been identified in cultures isolated from primary human prostatic stromal cells (Zhao & Peehl 2009). While the authors of this study concluded that these cells did not represent MSCs, it should be noted that CD90hi cells were only compared with CD90lo, rather than CD90-negative cells. Additionally, the differentiation potential of these two CD90-positive populations was not investigated. We would suggest that both these populations likely represent MSCs, albeit potentially ones at different stages of differentiation or lineage commitment. Our own studies clearly indicate the presence of MSCs in multiple primary prostate cancer specimens obtained directly from the operating room prior to expansion in tissue culture (Brennen et al. 2013). While CD90 expression has been proposed as a potential cancer biomarker (True et al. 2010), the relationship between CD90 expression and PIA or PIN, which are believed to be prostate cancer precursor lesions, has not been studied. Coupled with other characteristic MSC markers, this would help to determine whether MSCs traffic to these inflammatory precursor lesions as an early event in prostate carcinogenesis.

**MSCs: effects on tumor progression and metastasis**

The role of MSCs in the pathogenesis of cancer is complex and likely related to the balance of competing pro- and anti-tumorigenic forces. Numerous mechanisms have been proposed to play a role in the ability of MSCs to promote tumor growth, including stimulation of proliferation, angiogenesis, and metastasis, in addition to the immunosuppressive properties described earlier. Co-inoculation of MSCs with tumor cells has been shown to increase xenograft growth in models of melanoma and lymphoma, in addition to colon, breast, and lung cancer (Bergfeld & DeClerck 2010, Klopp et al. 2011). Tumor growth can be further fueled by promoting an increased tumor vasculature through the secretion of pro-angiogenic factors by MSCs, including VEGF, TGF-β, platelet-derived growth factor (PDGF), and basic fibroblast growth factor (bFGF) (Bergfeld & DeClerck 2010, Bianchi et al. 2011). MSCs are also frequently found in perivascular niches and can promote vessel stabilization through pericyte-like functions (da Silva Meirelles et al. 2006, Crisan et al. 2008, Bianchi et al. 2011). Additionally, MSCs have been shown to enhance the metastatic potential of breast and colon cancer cells in xenograft models.

Degree of Inflammation & Immunological Response

Immuno-Stimulatory Effects

Immuo-Suppressive Effects

**Figure 3**

The dichotomous role of MSCs in modulating the immune response depends on the degree of the immunological assault. Evidence suggests that during the initial stages of an inflammatory response, MSCs can behave as antigen-presenting cells and have immunostimulatory effects that activate an adaptive immune response following PAMP recognition and IFN-γ stimulation. As concentrations of IFN-γ, TNFs, and other inflammatory cytokines rise during prolonged inflammation and the lymphocyte-to-MSC ratio increases, the immunosuppressive properties gain dominance and serve as a negative feedback mechanism to prevent unchecked chronic inflammation that can contribute to pathogenesis. A full colour version of this figure is available via http://dx.doi.org/10.1530/ERC-13-0151.
(Karnoub et al. 2007, Klopp et al. 2011), in addition to promoting a pro-tumorigenic environment in the bone marrow (Bergfeld & DeClerck 2010). The immunosuppressive properties of MSCs have also been proposed as a mechanism to enable the tumor to escape host immune surveillance (Bergfeld & DeClerck 2010). Extensive reviews on the relationship between MSCs and cancer have previously been published elsewhere (Bergfeld & DeClerck 2010, Bianchi et al. 2011, Klopp et al. 2011).

While the pro-tumorigenic role of MSCs is more easily understood, there are also a large number of studies demonstrating anti-tumorigenic effects of MSCs for reasons that are less clear (Klopp et al. 2011) but include pro-inflammatory effects and the downregulation of survival signals mediated through the Akt and Wnt pathways (Ohlsson et al. 2003, Khakoo et al. 2006, Qiao et al. 2008). An attempt to reconcile these conflicting observations has recently been discussed by Marini and colleagues, who conclude that there is currently no clear explanation for these divergent findings (Klopp et al. 2011). The dichotomous role of MSCs in the immune system likely plays a role in this tumorigenic response; however, both pro- and anti-tumorigenic effects have been observed in both immunocompromised and immunocompetent animals, suggesting that this relationship is more complex than merely a function of their immunomodulatory properties.

**MSCs: role in prostate carcinogenesis**

Specifically, with regard to MSCs and prostate cancer, several *in vitro* investigations have attempted to understand how the interactions between these two cell types may contribute to carcinogenesis in both the primary and the metastatic tumor microenvironments (Fig. 1). FGF-9 and paracrine factors secreted by bone metastatic PC3 cells stimulate osteoblastic differentiation of human BM-MSCs, whereas conditioned medium from non-metastatic CWR22Rv1 cells did not (Fritz et al. 2011). This is particularly interesting in light of the well-known observation that prostate cancer frequently generates osteoblastic lesions when it metastasizes to the bone. Later studies demonstrated that the pro-osteoblastic effect of PC3-conditioned media (PC3-CM) was due to the presence of epidermal growth factor receptor (EGFR) ligands, which also stimulated the proliferation of human BM-MSCs, but suppressed adipocyte and osteoclast differentiation (Borghese et al. 2012). Interestingly, significant levels of new bone formation *in vivo* were only observed when MSCs were injected intra-tibially in the presence of PC3 cancer cells but not in their absence (Chanda et al. 2009). PC3-CM also stimulated IL6 and CCL5 secretion by MSCs, the latter of which led to increased cell migration; reciprocally, MSCs not only promoted PC3 proliferation and colony formation but also protected them from docetaxel-induced toxicity through paracrine mediators (Borghese et al. 2012). Of note, in response to radiation and cytotoxic chemotherapies, stromal cells in the prostate tumor microenvironment were recently shown to secrete paracrine factors, including WNT16B, that promote the survival of adjacent cancer cells and lead to enhanced therapeutic resistance (Sun et al. 2012). Ye et al. (2012) have shown that media conditioned by human BM-MSCs not only upregulates MMP-2/-9 expression in PC3 cells but also promotes their migration and invasion via TGF-β signaling pathways. Additionally, oncostatin M was recently shown to induce both TGF-β1 and periostin expression in human ADSCs and promote PC3 adhesion (Lee et al. 2013).

To date, there have only been a limited number of studies investigating the effect of MSCs on prostate tumor growth *in vivo*, and the majority of these have demonstrated little to no effect (Table 1). It should be mentioned, however, that most of these studies have utilized the PC3 cell line, and therefore, these analyses should be extended into other models before making generalized conclusions. Khakoo et al. (2006) demonstrated that human BM-MSCs suppress tumor growth in a model of Kaposi’s sarcoma by inhibiting Akt activation in a cell contact-dependent manner; however, when co-cultured with PC3 cells, these same MSCs had no effect on phospho-Akt levels, nor did they alter xenograft growth in immunocompromised animals. No effect on tumor weight or animal survival was observed in mice bearing PC3 tumors who received three weekly i.v. injections of 2×10⁶ human BM-MSCs (Wang et al. 2012). Rat BM-MSCs transduced with the herpes simplex virus thymidine kinase gene (HSV-TK) had no effect on PC3 xenograft growth in the absence of ganciclovir treatment (Song et al. 2011). Additionally, human BM-MSCs had no effect on tumor take or growth rates when co-injected with DU145 cells (Pessina et al. 2011). A study by Zhang et al. (2011) demonstrated that rat BM-MSCs injected into already established tumors had no effect on PC3 xenograft growth. Additionally, C3H10T1/2 embryonic murine MSCs co-injected with PC3 cells also had no effect on intratibial tumor growth (Fritz et al. 2008). By contrast, Chanda et al. (2009) showed that adult murine MSCs injected into already established intratibial PC3 tumors suppressed their growth and promoted bone regeneration, although the effect was less pronounced than when the MSCs were co-injected with the tumor cells simultaneously. Using the
### Table 1: Effects of MSCs on prostate cancer growth in preclinical animal models

<table>
<thead>
<tr>
<th>Effect on tumor growth</th>
<th>Species (MSC)</th>
<th>Tissue source</th>
<th>Mouse strain</th>
<th>Tumor model</th>
<th>Immunogenicity</th>
<th>MSC: cancer cell ratio (no. of MSCs)</th>
<th>Delivery route</th>
<th>Timing (post-inoculation)</th>
<th>MSC injections (#)</th>
<th>Results</th>
<th>Proposed mechanism</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>−</td>
<td>Human</td>
<td>Bone marrow</td>
<td>SCID</td>
<td>PC3</td>
<td>Allogeneic</td>
<td>1:6.7 (3 × 10^5)</td>
<td>MSC: i.v.; tumor: s.c.</td>
<td>d14, 21, 28 + (35 and 42) d0, 3, and 10</td>
<td>3</td>
<td>No effect on tumor growth or survival</td>
<td>None proposed</td>
<td>Wang et al. (2012)</td>
</tr>
<tr>
<td>−</td>
<td>Human</td>
<td>Bone marrow</td>
<td>Nude</td>
<td>PC3</td>
<td>Allogeneic</td>
<td>1:12.5 (4 × 10^5)</td>
<td>MSC: i.v.; tumor: s.c.</td>
<td>d0 (co-inoculation)</td>
<td>1</td>
<td>No effect on tumor growth</td>
<td>None proposed</td>
<td>Khakoo et al. (2006)</td>
</tr>
<tr>
<td>−</td>
<td>Human</td>
<td>Bone marrow</td>
<td>NOD/SCID</td>
<td>DU145</td>
<td>Allogeneic</td>
<td>1:5 (0.4 × 10^5)</td>
<td>MSC: s.c.; tumor: s.c.</td>
<td>d0 (co-inoculation)</td>
<td>1</td>
<td>No effect on tumor growth</td>
<td>None proposed</td>
<td>Pessina et al. (2011)</td>
</tr>
<tr>
<td>−</td>
<td>Human</td>
<td>Adipose</td>
<td>Nude</td>
<td>PC3-M</td>
<td>Allogeneic</td>
<td>1:1 (1 × 10^5)</td>
<td>MSC: s.c.; tumor: s.c.</td>
<td>s.c.: d0 (co-inoculation) i.v.: d7 and d18</td>
<td>1 or 2</td>
<td>Increased tumor growth</td>
<td>None proposed</td>
<td>Zolochevska et al. (2012)</td>
</tr>
<tr>
<td>†</td>
<td>Human</td>
<td>Adipose</td>
<td>Nude</td>
<td>PC3</td>
<td>Allogeneic</td>
<td>1:2 (1 × 10^5)</td>
<td>MSC: s.c. (left flank); tumor: s.c. (right flank)</td>
<td>d7</td>
<td>1</td>
<td>Increased tumor growth</td>
<td>CXCL12/CXCR4 axis; increased capillary density; FGF2 expression</td>
<td>Lin et al. (2010)</td>
</tr>
<tr>
<td>†</td>
<td>Human</td>
<td>Adipose</td>
<td>Nude</td>
<td>MDA-PCa-11Bb</td>
<td>Allogeneic</td>
<td>1:10 (1 × 10^5)</td>
<td>MSC: s.c.; tumor: s.c.</td>
<td>d0 (co-inoculation)</td>
<td>1</td>
<td>Increased tumor growth</td>
<td>None proposed</td>
<td>Prantl et al. (2010)</td>
</tr>
<tr>
<td>†</td>
<td>Human</td>
<td>Bone marrow</td>
<td>Nude</td>
<td>PC3</td>
<td>Allogeneic</td>
<td>1:5 (1 × 10^5)</td>
<td>MSC: s.c.; tumor: s.c.</td>
<td>d0 (co-inoculation)</td>
<td>1</td>
<td>Increased tumor growth</td>
<td>None proposed</td>
<td>Ye et al. (2012)</td>
</tr>
<tr>
<td>†</td>
<td>Human</td>
<td>Bone marrow</td>
<td>SCID</td>
<td>PC3</td>
<td>Allogeneic</td>
<td>1:100 (2 × 10^5)</td>
<td>MSC: s.c.; tumor: s.c.</td>
<td>d10</td>
<td>1</td>
<td>Increased tumor growth</td>
<td>None proposed</td>
<td>Jung et al. (2013)</td>
</tr>
<tr>
<td>†</td>
<td>Mouse</td>
<td>Bone marrow</td>
<td>SCID</td>
<td>PC3</td>
<td>Allogeneic</td>
<td>5:1 (5 × 10^5)</td>
<td>MSC: I.T.; tumor: I.T.</td>
<td>d1 or d14</td>
<td>1</td>
<td>Suppressed tumor growth effect less pronounced in established tumors; promoted bone regeneration in the presence of cancer cells</td>
<td>New bone formation restricted growth of cancer cells</td>
<td>Chanda et al. (2009)</td>
</tr>
<tr>
<td>−</td>
<td>Mouse</td>
<td>Bone marrow</td>
<td>SCID</td>
<td>PC3</td>
<td>Allogeneic</td>
<td>1:1 and 3:1 (0.5 and 1.5 × 10^5)</td>
<td>MSC: I.T.; tumor: I.T.</td>
<td>d0 (co-inoculation)</td>
<td>1</td>
<td>No effect on tumor growth at either ratio</td>
<td>None proposed</td>
<td>Fritz et al. (2008)</td>
</tr>
<tr>
<td>−</td>
<td>Mouse</td>
<td>Bone marrow</td>
<td>C57BL/6</td>
<td>TRAMP-C2</td>
<td>Syngeneic</td>
<td>1:2.5 (2 × 10^5)</td>
<td>MSC: i.v.; tumor: i.v.</td>
<td>d10</td>
<td>1</td>
<td>No effect on lung metastasis</td>
<td>None proposed</td>
<td>Ren et al. (2008a,b)</td>
</tr>
<tr>
<td>−</td>
<td>Mouse</td>
<td>Adipose</td>
<td>C57BL/6</td>
<td>TRAMP-C2-Ras</td>
<td>Syngeneic</td>
<td>1:5 (4 × 10^5)</td>
<td>MSC: i.v.; tumor: s.c.</td>
<td>d0 (co-inoculation)</td>
<td>1</td>
<td>No effect on tumor growth</td>
<td>None proposed</td>
<td>Zolochevska et al. (2012)</td>
</tr>
<tr>
<td>−</td>
<td>Rat</td>
<td>Bone marrow</td>
<td>Nude</td>
<td>PC3</td>
<td>Allogeneic</td>
<td>1:20 (1 × 10^5)</td>
<td>MSC: i.v.; tumor: s.c.</td>
<td>d3 and 10</td>
<td>2</td>
<td>No effect on tumor growth</td>
<td>None proposed</td>
<td>Song et al. (2011)</td>
</tr>
<tr>
<td>−</td>
<td>Rat</td>
<td>Bone marrow</td>
<td>Nude</td>
<td>PC3</td>
<td>Allogeneic</td>
<td>1:1 (2 × 10^5)</td>
<td>MSC: I.T.; tumor: s.c.</td>
<td>d14, 21, and 28</td>
<td>3</td>
<td>No effect on tumor growth</td>
<td>None proposed</td>
<td>Zhang et al. (2011)</td>
</tr>
</tbody>
</table>
TRAMP-C2 model, Ren et al. (2008a) demonstrated that murine BM-MSCs had no effect on lung metastasis when injected 10 days post-tumor cell inoculation. Zolochevska et al. (2012) showed that human ADSCs had no effect on PC3 xenograft growth in immunocompromised animals nor did murine ADSC significantly stimulate xenograft growth in the immunocompetent TRAMP-C2-Ras model. Lee et al. (2013) also demonstrated that co-inoculation of human ADSC had no effect on PC3-M xenograft growth in the absence of oncostatin M.

By contrast, Lin et al. (2010) showed that implanted ADSCs were recruited to PC3 xenografts on the opposite flank via the CXCL12/CXCR4 axis where they stimulated tumor growth, at least partially through enhanced angiogenesis and FGF2 expression. A study by Cavarretta et al. (2010) also suggested that unmodified human ADSCs co-injected subcutaneously with PC3 cells accelerated tumor growth and mortality by a few days; however, systemically administered ADSCs expressing cytosine deaminase (CD) significantly suppressed PC3 tumor growth even in the absence of 5-fluorocytosine (5-FC) treatment. Additionally, Prantl et al. (2010) reported increased tumor growth when MDA-PCA-118b cells were co-inoculated with human ADSCs. In contrast to previous reports, Ye et al. (2012) observed a significant increase in tumor volumes when PC3 cells were co-injected with human BM-MSCs. Taichman and colleagues recently reported that human BM-MSC stimulated PC3 xenograft growth when co-inoculated at ratios of 1:100 through a CXCR6/CXCL16-dependent mechanism (Jung et al. 2013). They further demonstrated that the recruitment of murine MSC to murine RM1 prostate cancer tumors in vivo was CXCL16 dependent and the number of MSCs present in the tumor correlated with tumor growth. Furthermore, CXCR6 signaling in BM-MSC induced their conversion to a CXCL12-expressing CAF phenotype, which has been implicated in prostate cancer metastasis (Jung et al. 2013).

These conflicting results regarding the influence of MSCs on prostate cancer growth may be due to differences in the ratio of MSCs to tumor cells, the absolute number of MSCs injected, or the timing of their administration relative to tumor inoculation. Furthermore, there does not seem to be a clear relationship between the immunogenicity of the MSCs and tumor cells used nor the immunological status of the xenograft hosts (Table 1). Of note, a recent study by Marini and colleagues suggested that local ADSCs were more likely to be integrated into the fibrovascular network of the early tumor, whereas their bone marrow-derived counterparts were more likely to be localized to the tumor periphery where they may play a role in tissue remodeling and metastasis (Kidd et al. 2012). Interestingly, there does seem to be a higher incidence of pro-tumorigenic effects observed in experiments using ADSCs compared with BM-MSCs in the prostate-specific studies described earlier and in those reviewed by Klopp et al. (2011), but this is not exclusively true.

Both ADSCs and BM-MSCs have also been shown to give rise to CAF (Fig. 1; Mishra et al. 2008, 2009, Paunescu et al. 2011, Kidd et al. 2012, Jung et al. 2013), which have been implicated in nearly all stages of prostate cancer carcinogenesis, including initiation, progression, invasion, and metastasis (Chung 1991, Olumi et al. 1999, Bhowmick et al. 2004, Franco et al. 2010, Giannoni et al. 2010, Brennen et al. 2012, Li et al. 2012). Human prostate-derived CAF co-implanted with initiated but non-tumorigenic human prostate epithelium into immunocompromised murine hosts significantly enhances tumor growth (Olumi et al. 1999). Loss of TGF-β responsiveness in fibroblasts through genetic manipulation results in murine PIN-like lesions (Bhowmick et al. 2004) and promotes mixed bone lesions in intratibial models of metastasis (Li et al. 2012). Conditioned media from activated fibroblasts promotes epithelial-to-mesenchymal transition in PC3 cells in vitro, in addition to stimulating invasiveness and prostasphere formation (Giannoni et al. 2010). These same authors went on to demonstrate that prostate-derived CAF enhanced PC3 aggressiveness in vivo by promoting tumor formation and facilitating lung micrometastases (Giannoni et al. 2010). The role of CAF in the progression of tumors from multiple tissues, including breast, colon, and pancreas in addition to the prostate, are well described and have been extensively reviewed elsewhere (Kalluri & Zeisberg 2006, Orimo & Weinberg 2006, Franco et al. 2010, Shimoda et al. 2010). Our own studies suggest that CAF derived from human prostates are enriched in MSCs (Brennen et al. 2013). These seemingly contradictory observations regarding the well-known tumor-promoting properties of CAF and the lack of any effect in the majority of the studies described earlier using MSCs serves to further reinforce the idea that MSCs isolated from different compartments have divergent phenotypes. Perhaps unsurprisingly, this implies that prostate-derived CAF are different than the BM-MSCs from which at least a subset of them is derived. These differences likely arise as a result of their developmental origin and distinct signaling events received through interactions with the tissue and tumor microenvironments in which they are found. Additionally, these CAF may pass through an ADSC intermediate stage depending on their mode of recruitment, which may further add to...
the complexity and heterogeneity observed in the phenotypic and functional differences observed in these cells (Kidd et al. 2012).

**MSCs: tumor-targeting vectors**

Available evidence strongly suggests that the inherent tropism of MSCs for tumor tissue can be exploited to deliver therapeutic and diagnostic agents. Indeed, much preclinical work has already been performed in this area using MSCs derived from a variety of species and tissue sources (Ciavarella et al. 2011, Shah 2012). In addition to the tumor-targeting properties of MSCs, their immuno-privileged nature suggests that large quantities of these cells can be harvested from a healthy donor, expanded, and manipulated *ex vivo* prior to infusion into multiple allogeneic patients as an ‘off-the-shelf’ therapy. This latter point not only makes this therapeutic strategy more practical with regard to time and cost but also alleviates ethical considerations related to re-infusing the cancer patient’s own (autologous) cells with regard to their potential to influence tumor malignancy.

A common theme of these strategies is to utilize genetic engineering techniques to generate MSCs that express various molecules with anticancer properties, which are then delivered to the tumor by the MSCs via systemic circulation. Generally, these MSC-delivered anticancer agents fall into one of several categories: immunostimulatory agents, oncolytic viruses, growth factor antagonists, pro-apoptotic factors, anti-angiogenic compounds, or prodrug-converting enzymes. Marini et al. pioneered the use of adenoviral transduced MSCs to deliver IFN-β to sites of cancer and have demonstrated efficacy in preclinical models of melanoma, breast, and pancreatic cancer (Studeny et al. 2002, 2004, Kidd et al. 2010). Delivery of IFN-β by genetically engineered MSCs has also shown efficacy in models of prostate bone and lung metastasis (Ren et al. 2008a, Chanda et al. 2009). Additional immunostimulatory agents, including IL2, IL7, IL12, IL18, and CX3CL1, have also been engineered into the MSC genome and used to treat a variety of preclinical cancer models, such as glioma, melanoma, Ewing’s sarcoma, and renal cell carcinoma (Nakamura et al. 2004, Elzaouk et al. 2006, Duan et al. 2009, Gao et al. 2010, Gunnarsson et al. 2010).

Multiple groups have also begun developing MSCs as delivery vectors for oncolytic viruses (Nakashima et al. 2010). Cell-based delivery of oncolytic viruses cannot only enhance the tumor-targeting potential of these viruses but can also reduce their neutralization by shielding them from pre-existing antiviral antibodies (Mader et al. 2009, Huang et al. 2013). Dembinski et al. (2010) demonstrated that delivery of a conditionally replicating fiber-modified adenoviral vector using MSCs reduced off-target infection and systemic toxicity following i.p. injection in a model of disseminated ovarian cancer. The Pereboeva and Curiel groups have also shown increased efficacy and survival following therapy with conditionally replicating adenovirus-transduced MSCs in ovarian xenograft and breast cancer lung metastasis models (Komarova et al. 2006, Stoff-Khalili et al. 2007).

The delivery of various prodrug-converting enzymes, including carboxylesterases, CD, and HSV-TK, have also generated provocative results in various preclinical models. Co-inoculation of MSCs expressing HSV-TK with PC3 prostate cancer cells inhibited xenograft growth when treated with ganciclovir, but not in its absence (Song et al. 2011). Furthermore, systemically delivered MSCs expressing HSV-TK showed efficacy against orthotopic pancreatic and hepatic xenograft growth and reduced the incidence of pancreatic metastasis (Zischek et al. 2009, Niess et al. 2011). Altaner and colleagues demonstrated that both co-inoculated and systemically administered ADSCs engineered to express CD significantly reduced tumor burden in animals bearing PC3 prostate cancer xenografts following daily doses of 5-FC (Cavarretta et al. 2010). This same group has also shown efficacy against HT-29 colon cancer and A375 melanoma xenograft growth *in vivo* using CD-transduced ADSCs (Kucerova et al. 2007, 2008). Additionally, MSCs engineered to express carboxylesterase, which metabolizes CPT-11 into an active topoisomerase I inhibitor (SN-38), have shown efficacy against mouse models of glioma (Yin et al. 2011, Choi et al. 2012).

Additional strategies seeking to utilize the tumor-targeting properties of MSCs include the delivery of pro-apoptotic factors, such as TRAIL (Grisendi et al. 2010, Shah 2012); anti-angiogenic agents, such as thrombospondin-1 (van Eekelen et al. 2010) and endostatin (Yin et al. 2011); and growth factor antagonists, such as NK4 (Kanehira et al. 2007). An interesting approach recently described by Spitzweg et al. permits both imaging and therapy to be performed using MSCs transfected with the sodium iodide symporter (NIS), which is normally responsible for concentrating iodide in the thyroid (Knoop et al. 2011). NIS expression not only resulted in selective accumulation of iodine in hepatocellular tumors in mice, which made both 123I scintigraphy and 124I PET imaging possible but also abrogated xenograft growth following systemic administration of the radionuclide 131I.
While these strategies have shown great promise in numerous preclinical models, none have entered into clinical trials yet, although the relatively short time frame since their inception precludes any judgment on their eventual clinical potential. In fact, the world’s first unmodified MSC therapy only received approval as recently as 2012 in Canada for the treatment of GVHD (Osiris Therapeutics 2012). However, one attribute of these approaches that may ultimately harm their clinical translation is the failure to take into consideration the trafficking of MSCs to multiple sites throughout the body in addition to the tumor following systemic infusion after the initial entrapment in the lung, including the spleen, kidneys, liver, bone marrow, and other sites of inflammation and remodeling (Gao et al. 2001, Devine et al. 2003, Allers et al. 2004, Detante et al. 2009, Choi et al. 2011, von Bahr et al. 2012). This may increase the off-target/non-tumor effects and systemic toxicity associated with these therapies following infusion. One strategy to circumvent these potential off-target effects is the use of MSCs to deliver prodrugs that are activated in a tumor- or tissue-specific manner. As one example, ongoing studies in our own laboratory in collaboration with multiple other groups are seeking to develop MSCs as vectors to deliver prostate-specific antigen (PSA)-activated prodrugs (Denmeade et al. 2003) and protoxins (Williams et al. 2007) to sites of metastatic prostate cancer using multiple therapeutic platforms, including nanoparticle-loading strategies and genetic manipulation (Brennen et al. 2013). In this therapeutic scenario, prodrugs delivered by MSCs to nontarget tissues will not be activated due to the lack of enzymatically active PSA, which is only present in the prostate and at sites of prostate cancer metastases, thereby reducing systemic toxicity. Additionally, Karp and colleagues have demonstrated that MSC homing and engraftment in inflamed tissue can be increased by decorating their surface with proteins involved in leukocyte extravasation (Sarkar et al. 2011). Cell engineering strategies such as this and continued optimization of viral transduction methods for MSCs (Lin et al. 2012) will help translate these strategies into the clinic more efficiently.

**Summary**

In summary, MSCs have emerged as critical regulators of the immune response. The role of these cells in both the innate and adaptive immunity is complex and has yet to be fully elucidated. MSCs have a multitude of immunosuppressive properties through effects on nearly every component of the immune system. Additionally, MSCs also have immunostimulatory effects on many of these same components under specific conditions, particularly during the initial phases of an immunological assault. The balance between these competing forces, which is dictated by IFN-γ and the rest of the inflammatory cytokine milieu, plays a role in numerous pathological maladies, including cancer. MSCs and their progeny have a complex role in tumor biology with both pro- and anti-tumorigenic effects being described. While the immunomodulatory properties of these cells certainly play an important role in this relationship, available evidence suggests that the whole story is far more complex and dependent on numerous interactions with other cells present in the tumor microenvironment, both static residents and dynamic infiltrators. However, despite the incomplete understanding of MSC physiology, current data strongly suggest that these cells have an inherent tropism for tumor tissue based on the inflammatory microenvironment frequently present. These tumor trafficking properties, immunoprivileged nature, and expansion capabilities have the potential for exploitation as a cell-based delivery vector for therapeutic and diagnostic purposes. Cell-based treatment modalities attempting to harness the bodies’ own physiology for therapeutic benefit have gained traction over the last few years in a variety of diseases and are sure to represent a growing trend in promising anticancer strategies of the future.

**Declaration of interest**

S R Denmeade and J T Isaacs have licensed PRX302 to and receive royalties from Sophiris Bio, Corp. Both these relationships for S R Denmeade and J T Isaacs have been disclosed and are under the management of the Johns Hopkins University School of Medicine Conflict of Interest Committee.

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**References**

Afzah H, Yang Z, Hui JH, Ouyang HW & Lee EH 2007 A comparison between the chondrogenic potential of human bone marrow stem cells...


Huang JI, Kazmi N, Durbhakula MM, Hering TM, Yoo JU & Johnstone B 2013 The use of hypoxic cultured mesenchymal stem cells for oncolytic virus therapy. Molecular Therapy 21 392–401. (doi:10.1038/mt.2011.93)


http://erc.endocrinology-journals.org
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Li Y & Lin F 2012 Mesenchymal stem cells are injured by complement after their contact with serum. *Blood* **120** 3436–3443. (doi:10.1182/blood-2012-03-420612)


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Zimmet JM & Hare JM 2005 Emerging role for bone marrow derived mesenchymal stem cells in myocardial regenerative therapy. Basic Research Cardiology 100: 471–481. (doi:10.1007/s00395-005-0553-4)


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