Cell-Based Therapies for Tissue Fibrosis

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The development of tissue fibrosis in the context of a wound-healing response to injury is common to many chronic diseases. Unregulated or persistent fibrogenesis may lead to structural and functional changes in organs that increase the risk of significant morbidity and mortality. We will explore the natural history, epidemiology, and pathogenesis of fibrotic disease affecting the lungs, kidneys, and liver as dysfunction of these organs is responsible for a substantial proportion of global mortality. For many patients with end-stage disease, organ transplantation is the only effective therapy to prolong life. However, not all patients are candidates for the major surgical interventions and life-long immunosuppression required for a successful outcome and donor organs may not be available to meet the clinical need. We will provide an overview of the latest treatment strategies for these conditions and will focus on stem or progenitor cell-based therapies for which there is substantial pre-clinical evidence based on animal models as well as early phase clinical trials of cell-based therapy in man.

Keywords: fibrosis, stem cells and regenerative medicine, cell therapy, mesenchymal stem cells, progenitor cells

INTRODUCTION

An appropriate response to injury is required for homeostasis. While injury may take many forms, the repair response is typically generic. An understanding of aberrant wound repair has direct relevance to human disease given that organ fibrosis has been estimated to contribute to 45% of all-cause human mortality (Wynn, 2004). While large, this statistic should not be surprising given the significance of fibrosis in chronic diseases affecting multiple organs (Table 1). Despite an extensive understanding of fibrogenesis in response to injury, no effective anti-fibrotic therapies are currently available. The highly conserved wound healing response is also highly redundant with multiple overlapping pathways suggesting that inhibition of a single candidate molecule or pathway is insufficient and new approaches are required. Based on this notion, cell-based therapies with the potential to alter multiple therapeutic targets are gaining popularity. A broad discussion of all stem cell types is beyond the focus of this mini-review. We will concentrate on mesenchymal stem cells (MSCs), which form the largest experience in cell therapy, as well as our work with placental stem cells.
LUNG FIBROSIS

Epidemiology, Burden of Disease, and Natural History

Pulmonary fibrosis is a family of over 200 chronic lung diseases stemming from multiple underlying causes including autoimmune diseases such as scleroderma and rheumatoid arthritis. Pulmonary fibrosis may be a consequence of environmental exposure to inhaled dust, bacteria, or molds, but can also arise following exposure to cancer treatments such as radiation therapy or chemotherapy using bleomycin or methotrexate. However, idiopathic pulmonary fibrosis (IPF), a type of pulmonary fibrosis where the cause is unknown occurs in 3–9 per 100,000 people annually based on conservative estimates from Europe and North America (Hutchinson et al., 2015). The incidence of IPF is increasing globally, comparable to many cancers (Hutchinson et al., 2015). A low incidence of IPF in some countries may reflect exclusion of milder cases or inconsistent classification. The severity of reported disease appears to be greater in East Asia, where the majority of cases were recorded as "unspecified interstitial lung disease" rather than IPF (Munakata et al., 1994; Ohno et al., 2008; Lai et al., 2012; Han et al., 2013).

Current Clinical Management

The clinical progression of IPF is often slow and gradual but an accelerated decline has been reported in some patients, associated with episodes of acute respiratory exacerbations. The median survival rates are historically poor at 2–3 years, with 5-year survival ranging between 30 and 50% (Bjoraker et al., 1998; Mapel et al., 1998; Rudd et al., 2007; Raghu et al., 2011). To date, lung transplantation remains the only intervention with proven benefit. Corticosteroid use is discouraged due to the association between steroid use and survival rates following acute exacerbations (Papiris et al., 2015).

While drugs such as nintedanib and pirfenidone appear to reduce disease progression, widespread usage is unlikely due to their high cost and conflicting data surrounding clinical efficacy. Currently, the proposed use of pirfenidone is to bridge between diagnosis and lung transplantation (Delanote et al., 2016). Nintedanib has also been found to prevent disease progression, and both drugs are comparable in terms of their estimated costs and health-related quality of life benefits (Rinciog et al., 2017). However, neither is curative and their cost is high (£100,000 per QALY). Thus, there is a need to identify alternative therapies.

Pathophysiology

Historically, IPF was believed to be an inflammatory disorder that progresses to fibrosis. The failure of anti-inflammatory and immunosuppressive therapeutic strategies triggered the need for reassessment (Selman et al., 2001; Raghu et al., 2012). The current consensus is that IPF is a consequence of multiple interacting genetic and environmental risk factors, with repeated damage and premature aging of alveolar epithelial cells (AECs) in genetically susceptible individuals (Wells and Maher, 2017). One robust genetic linkages to IPF is MUC5B polymorphism; however, the role of this gene in IPF pathogenesis remains undefined (Conti et al., 2016; Nakano et al., 2016). Unsurprisingly, the prototypic pro-fibrotic transforming growth factor-β (TGFβ) plays a central role in IPF, and while its function is well described, the source of excess TGFβ and activation of its latent form are poorly understood. A recent study by Froese et al. (2016) uncovered a role for mechanotransduction in TGFβ activation, unique to fibrotic lungs, suggesting that the physical stiffness of IPF lungs and mechanical forces applied to fibrotic lungs may contribute to disease perpetuation. Premature aging, telomere shortening, and alveolar senescence are also thought to contribute to IPF pathogenesis. Telomere dysfunction in AECs but not collagen-producing cells is responsible for age-related lung fibrosis (Naikawadi et al., 2016). When telomere dysfunction was conditionally induced in type 2 AECs (AEC2) in mice, an AEC2-induced cytokine response was detected when challenged with bleomycin, a 100% mortality rate was observed, supporting the critical role of telomere function in AEC2 for alveolar repair (Alder et al., 2015). When telomere dysfunction was conditionally induced in type 2 AECs (AEC2) in mice, an AEC2-induced cytokine response was detected when challenged with bleomycin, a 100% mortality rate was observed, supporting the critical role of telomere function in AEC2 for alveolar repair (Alder et al., 2015). Given the role of AEC2 as alveolar progenitor cells, Adler et al. concluded that alveolar stem cell failure might contribute to lung fibrosis. These observations have led some to postulate that a regenerative approach is required (Chambers and Hopkins, 2013).

Cell Therapies for IPF

To date there are six Phase I/II clinical trials (ClinicalTrials.gov) using stem cells for IPF, predominantly allogeneic bone marrow-derived MSCs (NCT01919827, NCT02594839, and NCT02013700). However, placenta and adipose tissue-derived MSCs have also been tested (NCT01385644 and NCT02135380). Interest in MSC-based therapies is attributed to their reported immunomodulatory and anti-fibrotic properties exerted through paracrine mediators. For example, there is recent evidence that

| Organ                  | Conditions                                                                 |
|-----------------------|----------------------------------------------------------------------------|
| Skin                  | Systemic sclerosis (may involve lung and kidney)                           |
|                       | Lupids, burns                                                             |
| Lung                  | Idiopathic pulmonary fibrosis                                             |
|                       | Interstitial lung disease (multiple aetiologies)                          |
|                       | Cystic fibrosis (may involve pancreas)                                    |
| Heart, blood vessels  | Congestive heart failure/cardiac fibrosis                                 |
|                       | Atherosclerosis (affects multiple organs)                                 |
| Liver                 | Cirrhosis (multiple aetiologies)                                          |
|                       | Hepatorenal fibrocystic diseases                                          |
| Intestine             | Crohn's disease                                                           |
|                       | Post-operative adhesions                                                  |
| Pancreas              | Chronic pancreatitis                                                      |
| Kidney                | End-stage renal disease (diabetes or hypertension)                        |
|                       | Renal interstitial fibrosis                                               |
| Immune system         | Chronic graft vs. host disease                                            |
| Musculo-skeletal system| Rheumatoid arthritis (may involve lung)                                   |
|                       | Ankylosing spondylitis                                                    |
|                       | IgG4-related retroperitoneal fibrosis                                     |
MSCs have immunomodulatory properties, and secrete replacement. In pre-clinical studies we have demonstrated modulate the immune response, ultimately allowing for cellular repair through paracrine and/or endocrine mechanisms that obtainable from bone marrow, and can be expanded in culture as a therapeutic tool as they are immunomodulatory, easily and promoting pro-regenerative mechanisms. MSCs are pursued Kidney Disease Potential of Cell-Based Therapies for of injury as seen in CKD (Schnaper et al., 2009). and homeostasis, unopposed expression results in a harmful cycle from the TGFβ pathway are essential for normal kidney development and homeostasis, unopposed expression results in a harmful cycle of injury as seen in CKD (Schnaper et al., 2009).

**KIDNEY FIBROSIS**

**Epidemiology and Pathogenesis of Fibrosis in Kidney Disease**

The epidemic of chronic kidney disease (CKD) and end-stage renal failure (ESRF) is a crisis for global healthcare. There is urgent need for new therapeutic options considering the high morbidity of dialysis, extensive healthcare costs, and donor-kidney shortages. Known risk factors for CKD include age, hypertension, obesity, and diabetes (McMahon et al., 2014).

Regardless of etiology, the common end-point of kidney injury is fibrosis leading to CKD development (Samarakoon et al., 2012). An excessive inflammatory and fibrotic response to injury results in decreased renal function as the renal tubules are damaged by scar tissue (Hewitson, 2009). Following initial renal injury, endogenous kidney cells release pro-inflammatory chemokines (Balasubramanian, 2013) that recruit inflammatory cells, activating fibroblasts, and causing tubular dilation (Meran and Steadman, 2011). The recruited immune cells release further inflammatory cytokines including those from the TGFβ superfamily and mitogen-activated protein kinases (MAPK/ERK) that activate fibrotic genes through SMAD signaling (Chevalier et al., 2010), leading to interstitial fibrosis and extracellular matrix accumulation. While inflammation and the TGFβ pathway are essential for normal kidney development and homeostasis, unopposed expression results in a harmful cycle of injury as seen in CKD (Schnaper et al., 2009).

**Potential of Cell-Based Therapies for Kidney Disease**

Stem or progenitor cell therapies offer a strategy for modulating CKD progression by suppressing multiple pathogenic pathways and promoting pro-regenerative mechanisms. MSCs are pursued as a therapeutic tool as they are immunomodulatory, easily obtainable from bone marrow, and can be expanded in culture for use in the clinic (Yagi et al., 2010). MSCs elicit endogenous repair through paracrine and/or endocrine mechanisms that modulate the immune response, ultimately allowing for cellular replacement. In pre-clinical studies we have demonstrated that MSCs have immunomodulatory properties, and secrete anti-inflammatory cytokines that promote inhibition of pro-inflammatory cytokines (Wise et al., 2014; Huuskes et al., 2015; Wise et al., 2016). MSCs have been used in experimental and clinical settings to improve diabetes and diabetic complications including kidney fibrosis. Recent clinical trials show that MSCs are safe and well tolerated in diabetes (Skyler et al., 2015); however, the diabetic microenvironment and/or comorbidities alter the quality or efficacy of MSCs following transplantation. Further mechanistic studies are needed to understand how MSCs protect against fibrotic injury and to improve efficacy following cell transplantation to overcome the transient clinical benefits that observed to date.

Endothelial progenitor cells (EPCs) also have therapeutic potential. EPCs can be mobilized from the bone marrow and adventitial tissue surrounding endothelial cells (ECs), and home toward sites of injury. There, they influence the release of vasoactive substances or directly differentiate into mature ECs to regenerate damaged endothelium. Diabetes-related EPC dysfunction is closely linked to the impaired healing response experienced by many patients with diabetic CKD. Circulating EPCs are low in type 2 diabetic patients and the loss of function of these cells may contribute to the vasodegenerative changes observed in diabetic micro- and macrovasculature disease (Schattenman et al., 2000). Therefore, harnessing the vascular reparative properties of EPCs represents a novel treatment for therapeutic revascularization and vascular repair for CKD patients with diabetes.

**Challenges to Reverse Kidney Fibrosis to Promote Repair**

A growing number of clinical trials show that MSCs are safe and well tolerated in diabetes (Skyler et al., 2015). The exogenous application of angiogenic-stimulating EPCs has shown promise for treatment of kidney failure, heart disease, and diabetes including retinopathy (Stitt et al., 2013). Both MSCs and EPCs mediate their effects largely through paracrine signaling and therefore require microenvironments that support optimal cell engraftment and proliferation. However, impediments in clinical translation occur due to low cell survival rates following transplantation that limit therapeutic efficacy (Chevalier et al., 2010). In particular, the fibrosis and chronic inflammation hamper cell survival and limit the cell integration into host tissue. Modulation and removal of the fibrotic lesion is therefore crucial to facilitate cell integration. In addition, the low number of transplanted cells retained at the site of injury also hampers stem cell efficacy.

To overcome these limitations, we recently reported a bimodal attack by combining MSC therapy and relaxin (RLX) to combat kidney fibrosis progression and aid in MSC survival (Huuskes et al., 2015). Combined MSCs and RLX administration in an obstructive nephropathy model significantly ameliorated kidney fibrosis, reduced macrophage infiltration, myofibroblast proliferation, and upregulated active MMP-2 compared to either therapy alone. This suggested that rather than inhibiting collagen accumulation, combination therapy induced significant collagen degradation. We provide evidence that RLX may influence
MSCs in vivo creating a more favorable environment for MSC-mediated repair (Huuskes et al., 2015). Targeting fibrosis resolution and limiting vascular damage may also be beneficial through combination therapy, as kidney function is dependent on adequate organ perfusion.

**LIVER FIBROSIS**

**Epidemiology, Burden of Disease, and Natural History**

Globally in 2013, cirrhosis was the 6th cause of life years lost in developed countries; ranging from 5th in Europe and central Asia, to 9th in southeast Asia and Oceania. In the United States, cirrhosis was the 12th leading cause of death overall and the 5th in adults aged 45–54 years (Heron, 2012). Common causes of chronic injury leading to cirrhosis include non-alcoholic steatohepatitis (NASH), alcohol use, and viral hepatitis. Hepatic fibrosis will progress to cirrhosis in many patients unless the cause of injury is removed. Progressive hepatic fibrosis and subsequent disruption of the hepatic vasculature by unregulated ECM expansion result in liver insufficiency characterized by jaundice, coagulopathy, and hypoalbuminemia. Portal hypertension leads to ascites, variceal hemorrhage, and hepatic encephalopathy. The onset of any of these conditions defines hepatic decompensation, which has a significantly higher 1-year mortality than compensated cirrhosis, 20% compared with 5% in one study of 700 patients (Zipprich et al., 2012). In these patients, the only treatment that alters long-term survival is liver transplantation. Unfortunately, not all patients are transplantation candidates and wait-list mortality remains a concern (Toniutto et al., 2016).

**Pathogenesis**

Hepatic fibrogenesis involves a dynamic interplay among hepatic stellate cells (HSCs), macrophages, and liver progenitor cells (LPCs). HSCs are pericytes that store vitamin A. During chronic liver injury, they transform to myofibroblasts, acquire a contractile phenotype, and accumulate at sites of injury where they secrete large amounts of ECM including collagen. TGFβ is a major fibrogenic cytokine that triggers HSC activation and ECM production and induces hepatocyte apoptosis (Gressner, 2002). Platelet-derived growth factor (PDGF) is the most potent mitogenic cytokine for HSC (Borkham-Kamphorst et al., 2007). These cytokines are logical targets for drug development. Blocking TGFβ and PDGF signaling has been effective in ameliorating experimental liver fibrosis (Yata et al., 2002; Liu et al., 2011), however, off-target effects hinder clinical development.

Kupffer cells (resident liver macrophages) and recruited circulating monocytes contribute to inflammation, fibrogenesis, and fibroblast resolution. Macrophages are capable of distinct activation states and functions, broadly classified as M1 (classical) or M2 (alternative) (Mantovani et al., 2004). M1 macrophages are classically pro-inflammatory, whereas M2 macrophages are responsible for immunomodulation and wound-healing responses. In addition a fibrolytic macrophage subset (Ly6C(lo)) that produces high levels of matrix metalloproteinases that contribute to ECM degradation has been described (Ramachandran et al., 2012).

LPCs are rare in healthy tissue but proliferate and differentiate into cholangiocytes or hepatocytes during chronic liver injury. The LPC response corresponds with the degree of liver injury (Lowes et al., 1999; Roskams et al., 2003) because, unlike hepatocytes, LPC resist the anti-proliferative actions of TGFβ (Nguyen et al., 2007). LPC express surface markers representative of their primitive, undifferentiated state such as Thy-1 (CD90), prominin (CD133), and pan-cytokeratin. A close physical relationship exists between HSC and LPC suggesting that the two cell types proliferate in tandem as HSC depletion significantly dampens the LPC response (Roskams, 2008; Ruddell et al., 2009). HSC produce soluble factors that increase LPC proliferation and hepatocyte differentiation (Nagai et al., 2002; Lin et al., 2008) and ECM proteins produced by HSC, such as laminin, may activate the LPC response (Kallis et al., 2011). Conversely, LPC produce lymphotoxin (LT), which recruits HSC through paracrine signaling (Ruddell et al., 2009). LPC also recruit macrophages via CCL2 and CX3CL1. Macrophage-derived TNF and LT, in turn, influence LPC response (Viebahn et al., 2010).

**Treatment of Hepatic Fibrosis**

The concept that hepatic fibrosis develops from a wound-healing response to chronic injury provides a rational basis for treatment. Diminishing liver injury by inhibiting chronic hepatitis B replication results in significant fibrosis regression in cirrhotic patients (Marcellin et al., 2013). Similar outcomes occur in patients with chronic hepatitis C infection (Hoefs et al., 2011). In diseases without specific therapy, a general anti-fibrotic approach might be useful. However, a recent trial of a monoclonal antibody against lysyl-oxidase-like 2, which mediates collagen cross-linkage, was not effective (Meissner et al., 2016). Considering the complex interactions involved in hepatic wound healing, cell-based therapy may provide a strategy to control inflammation, degrade collagen, and promote hepatic parenchymal regeneration. Human clinical trials have utilized MSC with variable cell doses, delivery routes, and administration frequency (Table 2). Trial endpoints commonly include liver tests, ascites volume, or clinical scores (Child–Pugh–Turcotte, model for end-stage liver disease). To date, outcomes have yet to translate into clinical practice. Furthermore, there is experimental evidence that bone marrow-derived MSC can contribute to hepatic fibrosis (Russo et al., 2006). MSCs as an anti-fibrotic therapy has been critically reviewed (Haldar et al., 2016).

We studied human amnion epithelial cells (hAECs), fetus-derived stem-like cells that arise prior to gastrulation and are easily isolated from the placenta, which is an abundant and ethically undisputed source. hAEC prevent and reverse inflammation and established fibrosis in immunocompetent animal models of liver injury (Manuelpillai et al., 2010), diminish myofibroblast activation, and skew hepatic macrophages toward a reparative phenotype (Manuelpillai et al., 2012). Similar effects are seen with cell-free conditioned media, suggesting that hAEC release factors responsible for the observed outcomes (Hodge
### TABLE 2 | Summary of reports from clinical trials assessing safety and efficacy of cell therapies for lung and liver fibrosis.

| Study | Number of patient treated/control | Cell type | Route | Number of cells transfused/number of injections | Functional benefit sustained to end of F/U period? | Safety |
|-------|-----------------------------------|-----------|-------|-----------------------------------------------|-----------------------------------------------|--------|
| **Clinical trials in lung fibrosis** | | | | | | |
| Tzouvelekis et al., 2013 | 14/0 | Autologous adipose stromal cells | Endobronchial | 0.5 × 10⁶/kg body weight single injection | No, 12 months | No serious side-effects or complications |
| Chambers et al., 2014 | 8/0 | Allogeneic placental MSC | Intravenous | 1 × 10⁶, 2 × 10⁶ kg body weight single injection | No, 6 months | One chest infection; one IPF exacerbation |
| Glassberg et al., 2016 | 9/0 | Allogeneic BM MSC | Intravenous | 20, 100, or 200 × 10⁶ single injection | Yes, 6 months | No serious side-effects or complications |
| **Clinical trials in liver fibrosis** | | | | | | |
| Terai et al., 2006 | 9/0 | Autologous BM | Peripheral IV | 2.21–8.05 × 10⁹ Avg. 5.2 × 10⁹ single injection | Significant decrease in average CPT at 4 and 24 weeks | All had fever (38°C) at 1 day post-therapy |
| Couto et al., 2011 | 8/0 | Autologous BM MNC | HA | 2–15 × 10⁸ single injection | Yes, 2 months | Fewer within 24 h after injection in 10 subjects (50%) |
| Amer et al., 2011 | 20/20 | Hepatocyte lineage from autologous BM MNC | Intrahepatic or intrasplenic | 5 mL of cell suspension (2 × 10⁸/mL) single injection | Yes, 6 months | |
| Peng et al., 2011 | 53/105 | Autologous BM | HA | 10⁶/mL, number transfused not stated | Yes, 3 and 9 months | No serious side-effects or complications |
| El-Ansary et al., 2012 | 15/10 | BM MNC nine undifferentiated six HC differentiated | Peripheral IV | 10⁶/kg (40% HLC, 60% MSC) single injection | Yes, 3 and 6 months | No safety evaluation |
| Zhang et al., 2012 | 31/15 | Umbilical cord MSC | Peripheral IV | 0.5 × 10⁶/kg body weight | Yes, 48 weeks | Four had fever 38°C at 2–6 h |
| Mohamadnejad et al., 2013 | 15/12 | BM MSC | Peripheral vein (30 min) | 195 million (120–295 million) single injection | No difference between treated and control | |
| Lukashyk et al., 2014 | 6/0 | BM MSC | Intrahepatic | 5 mL suspension, 1 × 10⁶/kg single injection | Yes, 1 and 6 months | No safety evaluation |
| Salama et al., 2014 | 20/20 | G-CSF, autologous BM MSC | Peripheral IV | 1 × 10⁶/kg body weight | Yes, 6 months | |
| Mohamadnejad et al., 2016 | 18/9 | Eight CD133⁺ nine BM MNC | Portal vein | 4.7 × 10⁶–9.17 × 10⁸ (averages) two injections | Yes, 3 months | No, 6 months No procedural complications |

et al., 2014). Liver fibrosis reduction also occurs in hAEC-treated mice given a “Western diet” high in lipids and fructose to model fatty liver disease (unpublished). A phase 1 safety trial is planned in patients with compensated cirrhosis.

**SUMMARY**

The global burden of end-stage fibrotic disease can be seen in the impaired survival of patients with IPF, diabetic CKD, and cirrhosis. Fortunately, the pathogenesis of fibrosis in response to injury is relatively well understood and remarkably similar in different organs, suggesting that an integrated approach may be possible. Control or removal of the injury stimulus should be the primary focus in preventing disease progression, yet for many control is incomplete or unachievable, thus the need for a broadly effective anti-fibrotic therapy that targets multiple fibrogenic pathways remains. Cell-based approaches employing stem cells that are easy to isolate and upscale to sufficient quantities for clinical use have been successfully characterized in animal models of organ fibrosis. While the outcomes of early phase clinical trials indicate that cell-based (primarily MSC) therapies are safe, efficacy data remain scarce. Consequently, cell-based therapies remain largely experimental. The lack of robust efficacy data...
may be due to the heterogeneity of MSC populations as well as limited agreement regarding differentiation state, doses, and administration regimens. Challenges remain in determining the goals of cell therapy – whether to supply sufficient cells to replace damaged parenchyma, to dampen inflammation with the aim of decreasing fibrosis, or to stimulate endogenous progenitor cells and repair processes. Furthermore, the ability to manufacture, transport, and store stem cells in a cost-effective manner must be considered. Clinical trials will continue to inform us about the most effective stem cell types on which to base therapy as well as the optimal dosages necessary to achieve a clinically meaningful reduction in fibrosis-related organ dysfunction.

REFERENCES

Alder, J. K., Barkauskas, C. E., Limjunyawong, N., Stanley, S. E., Kembou, F., Tuder, R. M., et al. (2015). Telomere dysfunction causes alveolar cell stem cell failure. Proc. Natl. Acad. Sci. U.S.A. 112, 5099–5104. doi: 10.1073/pnas.1504780112

Amer, M. E., El-Sayed, S. Z., El-Kheir, W. A., Gabr, H., Gomaa, A. A., El-Alder, J. K., Barkauskas, C. E., Limjunyawong, N., Stanley, S. E., Kembou, F., Tuder, R. M., et al. (2015). Telomere dysfunction causes alveolar cell stem cell failure. Proc. Natl. Acad. Sci. U.S.A. 112, 5099–5104. doi: 10.1073/pnas.1504780112

AUTHOR CONTRIBUTIONS

WS contributed the liver fibrosis section; RL contributed the lung fibrosis section; SR contributed the kidney fibrosis section; and all authors reviewed the manuscript and provided critical intellectual input.

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Mantovani, A., Sica, A., Sozzani, S., and Allavena, P. (2004). The chemokine system in diverse forms of macrophage activation and polarization. Trends Immunol. 25, 677–686. doi: 10.1016/jUCCESS.2004.09.015

Manuelpillai, U., Lourensz, D., Vaghjiani, V., Tchongue, J., Lacey, D., Tee, J. Y., et al. (2010). Transplantation of human amnion epithelial cells reduces hepatic fibrosis in immunocompetent CCl\(_4\)-treated mice. Cell Transplant. 19, 1157–1168. doi: 10.3727/09668910X3049496

Manuelpillai, U., Locurcio, J., Lourensz, D., Vaghjiani, V., Samuel, C. S., Liu, A., et al. (2010). Ovarian cell transplantation in patients with HIV-related liver cirrhosis. J. Clin. Transl. Hepatol. 2, 217–221. doi: 10.14218/JCTH.2010.00027

Marcellin, P., Gane, E., Buti, M., Afdhal, N., Sievert, W., Jacobson, I. M., et al. (2013). Regression of cirrhosis during treatment with tenofovir disoproxil fumarate for chronic hepatitis B: a 5-year open-label follow-up study. Lancet 383, 468–475. doi: 10.1016/S0140-6736(13)61425-1

McMahon, G. M., Preis, S. R., Hwang, S. J., and Fox, C. S. (2014). Mid-adulthood risk factor profiles for CKD. J. Am. Soc. Nephrol. 25, 2633–2641. doi: 10.1681/ASN.2013070570

Meissner, E., McLaughlin, M., Matthews, L., Gharib, A., Wood, B., Levy, E., et al. (2016). Simtuzumab treatment of advanced liver fibrosis in HIV and HCV-infected adults: results of a 6-month open-label safety trial. Liver Int. 36, 1783–1792. doi: 10.1111/liv.13177

Meran, S., and Steadman, R. (2011). Fibroblasts and myofibroblasts in renal fibrosis. Int. J. Exp. Pathol. 92, 158–167. doi: 10.1111/j.1365-2613.2011.00764.x

Mohamadnejad, M., Vosough, M., Moossavi, S., Nikfam, S., Mardpour, S., Abrahamsson, T., et al. (2014). TGF-β1 signal transduction in chronic kidney disease. J. Am. Soc. Nephrol. 25, 1490–1496. doi: 10.1111/jnss.12228

Mohamadnejad, M., Vosough, M., Moossavi, S., Nikfam, S., Mardpour, S., Abrahamsson, T., et al. (2014). Intraperitoneal injection of bone marrow mononuclear or CD133+ cells in patients with decompensated cirrhosis: a double-blind randomized controlled trial. Stem Cells Transl. Med. 5, 87–94. doi: 10.5966/scb.2015-0004

Munakata, M., Askawa, M., Hama, Y., and Kawakami, Y. (1994). Present status of idiopathic intestinal pneumonia—from epidemiology to etiology. Nihon Kyobu Shikkan Gakkai Zasshi 32(Suppl.), 187–192.

Nagai, H., Terada, K., Watanabe, G., Ueno, Y., Aiba, N., Shibuya, T., et al. (2002). The role of TGF-β1 in the development of liver fibrosis. Hepatol. Res. 18, 217–225. doi: 10.1111/j.1440-1843.2002.00115.x

Skyler, J. S., Fonseca, V. A., Segal, K. R., Rosenstock, J., and MSB-DM003 Investigators. (2015). Allogeneic mesenchymal stem cell transplantation in Type 2 diabetes: a randomized, placebo-controlled, dose-escalation safety
and tolerability pilot study. *Diabetes Care* 38, 1742–1749. doi: 10.2337/dc14-2830

Stitt, A. W., Lois, N., Medina, R. J., Adamson, P., and Curtis, T. M. (2013). Advances in our understanding of diabetic retinopathy. *Clin. Sci.* 125, 1–17. doi: 10.1042/CS20120088

Terai, S., Ishikawa, T., Omori, K., Aoyama, K., Marumoto, Y., Urata, Y., et al. (2006). Improved liver function in patients with liver cirrhosis after autologous bone marrow cell infusion therapy. *Stem Cells* 24, 2292–2298. doi: 10.1634/stemcells.2005-0542

Toniutto, P., Zanetto, A., Ferrarese, A., and Burra, P. (2016). Current challenges and future directions for liver transplantation. *Liver Int.* 37, 317–327. doi: 10.1111/liv.13255/full

Tzouvelekis, A., Paspaliaris, V., Koliakos, G., Ntolios, P., Bouros, E., Oikonomou, A., et al. (2013). A prospective, non-randomized, no placebo-controlled, phase Ib clinical trial to study the safety of the adipose derived stromal cells-stromal vascular fraction in idiopathic pulmonary fibrosis. *J. Transl. Med.* 11:171. doi: 10.1186/1479-5876-11-171

Viebahn, C. S., Benseler, V., Holz, L. E., Elsegood, C. L., Vo, M., Bertolino, P., et al. (2010). Invading macrophages play a major role in the liver progenitor cell response to chronic liver injury. *J. Hepatol.* 53, 500–507. doi: 10.1016/j.jhep.2010.04.010

Wells, A. U., and Maher, T. M. (2017). Update in interstitial lung disease 2016. *Am. J. Respir. Crit. Care Med.* 196, 132–158. doi: 10.1164/rccm.201702-0351UP

Wise, A. F., Williams, T. M., Klewlet, M. B., Payne, N. L., Slatskas, C., Samuel, C., et al. (2014). Human mesenchymal stem cells alter macrophage phenotype and promote regeneration via homing to the kidney following ischemia-reperfusion injury. *Am. J. Physiol. Renal Physiol.* 306, F1222–F1235. doi: 10.1152/ajprenal.00675.2013

Wise, A. F., Williams, T. M., Rudd, S., Wells, C. A., Kerr, P. G., and Ricardo, S. D. (2016). Human mesenchymal stem cells alter the gene profile of monocytes from patients with Type 2 diabetes and end-stage renal disease. *Regen. Med.* 11, 145–158. doi: 10.2217/rme.15.74