REVIEW ARTICLE

Cell-based therapeutic strategies for multiple sclerosis

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The availability of multiple disease-modifying medications with regulatory approval to treat multiple sclerosis illustrates the substantial progress made in therapy of the disease. However, all are only partially effective in preventing inflammatory tissue damage in the central nervous system and none directly promotes repair. Cell-based therapies, including immunoablation followed by autologous hematopoietic stem cell transplantation, mesenchymal and related stem cell transplantation, pharmacologic manipulation of endogenous stem cells to enhance their reparative capabilities, and transplantation of oligodendrocyte progenitor cells, have generated substantial interest as novel therapeutic strategies for immune modulation, neuroprotection, or repair of the damaged central nervous system in multiple sclerosis. Each approach has potential advantages but also safety concerns and unresolved questions. Moreover, clinical trials of cell-based therapies present several unique methodological and ethical issues. We summarize here the status of cell-based therapies to treat multiple sclerosis and make consensus recommendations for future research and clinical trials.

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Abbreviations: ATG = antithymocyte globulin; BEAM = carmustine, etoposide, cytarabine, melphalan; Cy = cyclophosphamide; DMT = disease-modifying therapy; EDSS = Expanded Disability Status Scale; I/AHSCT = immunoablation followed by autologous hematopoietic stem cell transplantation; iPSC = induced pluripotent stem cell; MSC = mesenchymal stem cell; OPC = oligodendrocyte progenitor cell

Introduction

With multiple approved disease-modifying therapies (DMTs), there is a broad range of options to treat relapsing-remitting multiple sclerosis (Ingwerson et al., 2016). However, less progress has been made in the treatment of progressive forms of the disease (Shirani et al., 2016). While the positive impact of treatment on reducing the frequency of relapses and accrual of relapse-related disability has been demonstrated, none of the currently available agents halt disease progression or directly promote repair of pre-existing CNS damage. Moreover, all of the approved
therapies have potential adverse events that may compromise safety or adherence. All are expected to be ongoing life-long therapies as long as they remain safe and effective. Consequently, there is an imperative for new therapies that (i) are more effective in relapsing-remitting multiple sclerosis, particularly for patients with highly active disease who are at substantial risk for future disability; (ii) are effective in slowing or preventing progression; (iii) have the potential to reverse disability; and (iv) can be used safely with fewer delivery and adherence concerns.

Cell-based therapies have generated substantial interest as potential approaches to address these gaps by working through various mechanisms: regenerating the defective immune system that underlies multiple sclerosis by immunoablation followed by autologous haematopoietic stem cell transplantation (I/AHSCT); modifying both immune reactions and endogenous repair mechanisms using mesenchymal stem cells (MSCs) and other stem cells from bone marrow, adipose tissue, placenta, or other tissues; pharmacologic manipulation of endogenous stem cells to enhance their reparative capabilities; or replacing damaged or lost myelin-making oligodendrocytes by transplantation of oligodendrocyte progenitor cells (OPCs) or OPC-like inducible pluripotent stem cells (iPSCs) (Sarkar and Scolding, 2016).

In this review, we discuss the biology and potential utility of these cell-based therapeutic approaches in multiple sclerosis; summarize the progress made to date on testing in multiple sclerosis; discuss practical, scientific, clinical, regulatory, and ethical concerns; and make recommendations for future studies to move this therapeutic area forward. The review is based on an extensive literature search related to cell-based therapies for multiple sclerosis and on discussions at a consensus workshop, the International Conference on Cell-Based Therapies for multiple sclerosis, held 19–21 November 2015 in Lisbon Portugal under the auspices of the International Advisory Committee for Clinical Trials in Multiple Sclerosis (see Appendix 1 and Supplementary material for a list of conference participants).

### Immunoablation followed by haematopoietic stem cell transplantation

#### Biological background and rationale

The rationale for I/AHSCT to treat multiple sclerosis is depletion of autoreactive effector cells with immunoablative agents (the conditioning regimen) followed by infusion of autologous haematopoietic stem cells to support immune system reconstitution with more normal immune function (Muraro et al., 2005; Muraro and Abrahamsson, 2010). Analysis of circulating lymphocytes after I/AHSCT demonstrates reduction of circulating autoreactive effector T cells, predominantly Th17 rather than Th1, and emergence of recent thymic emigrants post-transplant, restoring a more regulatory milieu (Muraro et al., 2005, 2014; Darlington et al., 2013; Arruda et al., 2015). The degree of reconstituted T cell repertoire variability is related to the intensity of the conditioning regimen (Muraro et al., 2014). Muraro et al. (2014) reported the presence, pre-transplant, of circulating mucosal-associated invariant T cells (MAITs) characterized by a CD8⁺, CD161hi phenotype (Abrahamsson et al., 2013). These MAITs exert a pro-inflammatory effect by promoting production of several cytokines thought to be associated with the pathogenesis of multiple sclerosis, including interferon-gamma and interleukin-17 (Lovett-Racke et al., 2011). After transplantation, there was a significant reduction of this population in the peripheral blood in parallel with an increase of regulatory CD4⁺, CD25hi, CD127⁻, FoxP3⁺ T cells. The initial benefit of I/AHSCT probably results from this and other comparable alterations in immune function. However, some studies have detected re-emergence of autoreactive effector cells despite a high intensity conditioning regimen and persistence of efficacy (Darlington et al., 2013). Thus, the mechanisms responsible for sustained benefit of I/AHSCT are less well understood.

### Practical/procedural background

#### Appropriate patients for I/AHSCT

Recognition of patients with multiple sclerosis most likely to benefit from I/AHSCT has evolved. Initial studies mainly enrolled patients with longstanding severe progressive multiple sclerosis, when inflammatory features are less prominent and neurodegeneration is the main underlying mechanism (Trapp and Nave, 2008). Benefit generally was modest, although some patients exhibited sustained slowing or stabilization of disability, but improvement in neurologic function was rarely seen (Burt et al., 2015; Mancardi et al., 2015). Also, patients with more severe neurologic disability had increased risk of adverse events (Mancardi and Saccardi, 2008). More recent studies (Table 1) focused on relapsing-remitting multiple sclerosis and demonstrated that patients with active inflammatory features appear to derive the most benefit from this approach (Burt et al., 2012; Saccardi et al., 2012; Muraro et al., 2017). As a result, the current recommendation is for studies of I/AHSCT to enrol patients with highly active relapsing-remitting multiple sclerosis reflected by clinical relapses and MRI lesion activity, time from diagnosis within 5 years, and suboptimal response to available regulatory-approved DMTs (Burt et al., 2012; Saccardi et al., 2012). These criteria apply to only a limited subset of patients with multiple sclerosis but help define those at high risk for future disability despite available therapy. These recommendations have been somewhat controversial, as they suggest a relatively aggressive therapeutic approach for patients who may have little established disability (Soelberg Sorensen, 2016).

An important determinant of transplant success is the ability of patients to tolerate the conditioning regimen. Disease-related factors not only affect efficacy but also tolerability. In cancer patients, those with more advanced
disease, either with active cancer at time of transplant or refractory to prior therapy, have a higher failure rate. This is not only due to inability to control the disease with higher doses of chemotherapy, but also the increase in transplant-related morbidity or mortality from the cumulative effect of prior treatments. Similarly, multiple sclerosis patients with more severe disability or progressive disease also tend to have higher rates of transplant-related morbidity and mortality (Mancardi and Saccardi, 2008; Muraro et al., 2017). The effects of prior multiple sclerosis DMTs on efficacy or safety of I/AHSCST are unknown.

In allogeneic haematopoietic stem cell transplantation for haematologic malignancies, the overall impact of the cancer on general health (the estimated the ability to work, perform activities of daily living and the need for hospitalization) is correlated with transplant outcome; lower performance scores are associated with higher post-transplant mortality. Similarly, the presence of key comorbid conditions also impacts transplant outcome. A high score on the Haematopoietic Cell Transplantation Comorbidity Index, which includes 17 items comprising past medical history (stroke, myocardial infarction, arrhythmia, autoimmune disease, prior solid tumours), end organ function (pulmonary, hepatic, renal and cardiac), and weight (obesity), is associated with increased post-transplant mortality (Mancardi et al., 2005, 2015; Elsawy and Sorror, 2016). Although comorbidities are less common in younger patients with multiple sclerosis, they have an important impact on multiple sclerosis disease outcomes (Marrie et al., 2015). Their effects on the efficacy or safety of I/AHSCST to treat multiple sclerosis have not been explored.

**Transplant procedure**

I/AHSCST should be viewed as a multi-step process that leads to a combined therapeutic effect in multiple sclerosis. Adverse effects also can occur at each step. The typical sequence includes mobilization of peripheral blood haematopoietic stem cells, immunoablation via administration of a conditioning regimen, then infusion of haematopoietic stem cells to promote haematologic reconstitution.

Granulocyte colony stimulating factor (G-CSF) or granulocyte-macrophage colony stimulating factor (GM-CSF) are often used alone to mobilize haematopoietic stem cells from the bone marrow to the peripheral blood in healthy volunteer donors in an allogeneic donor transplant setting, but may cause worsening of neurologic manifestations in multiple sclerosis, either accentuation of pre-existing symptoms due to fever or *bona fide* relapses (Openshaw et al., 2000). Therefore, in multiple sclerosis, the most common approach is administration of cyclophosphamide (Cy) plus G-CSF as a mobilizing agent, which helps deplete lymphocytes that will eventually be collected in the graft and lessens the chance of reinfusion of autoreactive T cells. Administration of Cy also may contribute to the therapeutic effect and adverse effects of I/AHSCST.

There are clear distinctions between the conditioning regimens used to treat malignancies and for non-malignant diseases such as multiple sclerosis. In the setting of AHSCST for malignancies, the conditioning regimen consists of high doses of chemotherapy to maximize disease control; the primary intent of subsequent haematopoietic stem cell infusion is to ‘rescue’ haematopoiesis. In the setting of allogeneic haematopoietic stem cell transplantation, the conditioning regimen can be classified within an intensity spectrum according to the type of chemotherapeutic agents and/or radiation selected, and their respective doses. High intensity regimens, also termed myeloablative, require haematopoietic stem cell infusion to prevent irreversible bone marrow damage. At the opposite end of the spectrum are lower intensity regimens, also termed non-myeloablative, which minimally affect haematopoiesis. Intermediate intensity regimens, also termed reduced intensity, fall in the middle of this spectrum. The indication, type of transplant, and population being treated determine the choice of regimen intensity. For example, in some instances for the same indication and transplant type, a high intensity regimen will be selected for patients younger than 65 years and a reduced intensity in patients older than 65 years. In general, high intensity regimens are selected to better control the cancer and minimize the risk of disease relapse, but are potentially associated with greater morbidity and mortality compared to lower intensity regimens.

In multiple sclerosis, like other autoimmune diseases, the optimal intensity of the conditioning regimen remains uncertain and is actively debated. The main objective is to balance lymphocyte depletion to eliminate pathologic autoimmunity with acceptable morbidity and mortality. The most commonly used conditioning regimen in multiple sclerosis has been BEAM (carmustine, etoposide, cytarabine and melphalan), which is considered an intermediate intensity regimen, combined with anti-thymocyte globulin (ATG) (Mancardi et al., 2012, 2015; Muraro et al., 2013; Burman et al., 2014; Nash et al., 2015; Shevchenko et al., 2015). High intensity regimens, such as total body irradiation and busulfan, were initially used in multiple sclerosis but were either abandoned or modified because of toxicity. Atkins et al. (2016) reported the use of high dose busulfan and Cy (Bu/Cy) with infusion of a T cell depleted (CD34* cell selection) autologous graft (Atkins et al., 2016). During the study, several modifications to the busulfan regimen were made to improve tolerability. The route of administration was switched from oral to intravenous, the dose was reduced (though still considered in the high dose range), and the target dose was adjusted based on the first busulfan dose pharmacokinetics. Conversely, Burt and colleagues (2009, 2015) have advocated a low intensity or non-myeloablative regimen—Cy or alemtuzumab followed by ATG—reporting good efficacy in relapsing-remitting multiple sclerosis with reduced toxicity and no mortality.

One potential concern with use of a less intense conditioning regimen is suboptimal multiple sclerosis disease control. One study demonstrated that recipients of non-myeloablative regimens had early reappearance of MRI
lesion activity post-transplant (Mancardi et al., 2012). It is possible that the intensity of the conditioning regimen may need to be tailored to the clinical situation, although consensus on how to identify patients early with aggressive multiple sclerosis and poor prognosis is lacking. Another consideration is whether the specific drug combination within regimens considered the same intensity is associated with differential outcomes. Muraro et al. (2017) analysed data on 281 transplant recipients with multiple sclerosis worldwide in a retrospective registry-based study. Conditioning regimens varied greatly and when they were grouped according to intensity, there was no correlation with outcome. This observation may have been due to most patients having progressive multiple sclerosis and the proportion of patients with relapsing-remitting multiple sclerosis was not sufficient to demonstrate differential efficacy. Thus, the optimal regimen, Cy/ATG, BEAM-ATG, or Bu/Cy remains uncertain and, based on the available data, all remain acceptable options.

It remains uncertain whether haematopoietic stem cell transplantation should be considered merely bone marrow rescue or if it contributes to the therapeutic benefit of I/AHSCT. While less intensive conditioning regimens may not necessitate haematopoietic stem cell transplantation, the infusion of haematopoietic stem cells serves two purposes: (i) to reduce morbidity by shortening the duration of pancytopenia; and (ii) to increase benefit by promoting immune reconstitution with broader clonal diversity without auto-reactivity. Characteristics of the graft have received relatively little attention in multiple sclerosis. Some studies have administered a largely unmanipulated graft (Burman et al., 2014; Burt et al., 2015; Mancardi et al., 2015). Other studies have positively selected CD34+ cells ex vivo to remove any residual lymphocytes in the graft (Nash et al., 2015; Atkins et al., 2016). This step adds to the technical complexity of the transplant procedure but reduces the risk of reinfusion of potentially autoreactive lymphocytes. If haematopoietic stem cell transplantation is not merely rescue after immune depletion but, in fact, contributes to the efficacy of the procedure, further work is needed to optimize mobilization and graft processing to maximize potency.

**Multiple sclerosis-related outcomes**

Evaluation of therapeutic outcomes in multiple sclerosis is complex. Assessment of the success of a therapeutic intervention is more difficult than in I/AHSCT for malignant diseases, where transplant-related mortality, all-cause mortality, and/or malignant disease recurrence often are used as outcomes. Because multiple sclerosis is associated with only modest shortening of life-span (Goodin et al., 2012), transplant-related mortality or all-cause mortality alone are not likely to be an informative efficacy outcome in studies of I/AHSCT in multiple sclerosis.

The outcomes most often used in multiple sclerosis clinical trials are relapses, confirmed worsening of disability measured by the Expanded Disability Status Scale (EDSS) or Multiple Sclerosis Functional Composite, MRI lesion activity and burden, and normalized whole brain volume (Cohen et al., 2012). As summarized in Table 1, these endpoints have been used in trials of I/AHSCT in multiple sclerosis (Mancardi et al., 2012, 2015; Muraro et al., 2013; Burman et al., 2014; Burt et al., 2015; Nash et al., 2015; Shevchenko et al., 2015; Atkins et al., 2016). Because of the potential risk associated with I/AHSCT and to distinguish its efficacy from that of available highly effective multiple sclerosis therapies, some workshop participants favoured a stringent outcome be utilized in future trials of I/AHSCT in multiple sclerosis, specifically event-free survival with a composite outcome comprising clinical relapses, MRI lesion activity (new/enlarged T2-hyperintense lesions or gadolinium-enhancing lesions), confirmed disability worsening, and normalized whole brain volume. Whether the specific definitions of the outcome components should be those used for so-called ‘no evidence of disease activity’ (NEDA) in previous studies (Havrdova et al., 2010; Giovannoni et al., 2015; Kappos et al., 2015; Rotstein et al., 2015), or modified, e.g. to account for delayed efficacy in a highly active study population, was not decided at the workshop. Other workshop participants felt that early inhibition of inflammatory activity (clinical relapses and MRI lesion activity) had uncertain relation to long-term disease outcome (University of California San Francisco MS-EPIC Team et al., 2016) and was not likely to distinguish I/AHSCT from available highly effective DMTs. They advocated focusing primarily on long-term disability accrual. Thus, an important issue, especially in relapsing-remitting multiple sclerosis, is how effectively I/AHSCT alters the long-term disease course, that is, delays or prevents development of progressive disease and disability accrual, compared to available therapies. This determination will require a randomized trial comparing I/AHSCT to DMTs with long-term follow-up. A related question is whether I/AHSCT affects the subsequent response to, or safety of, DMTs administered.

An additional efficacy outcome potentially relevant for clinical trials of I/AHSCT is confirmed improvement in disability, which has been demonstrated in trials of several multiple sclerosis DMTs (Jones et al., 2010; Phillips et al., 2011; Hauser et al., 2015). Similarly, reversal of pre-existing disability also has been reported with I/AHSCT (Burt et al., 2015; Atkins et al., 2016). Although it is possible these interventions directly stimulate repair to some degree, it is more likely they unmask intrinsic repair mechanisms by effectively suppressing ongoing inflammatory damage (Chang et al., 2002, 2008, 2012).

**Financial cost**

The annual costs of multiple sclerosis DMTs range from ~$50 000 to $70 000 (Hartung et al., 2015) in the USA. The cost of I/AHSCT is ~$120 000 in the USA, which is incurred mainly in the first year with minimal direct costs subsequently. Thus, in contrast to DMTs for which cost accrues indefinitely, the financial cost of I/AHSCT is largely
<table>
<thead>
<tr>
<th>Study and study period</th>
<th>Design</th>
<th>n</th>
<th>Study population</th>
<th>EDSS median (range)</th>
<th>Mobilization</th>
<th>Conditioning regimen</th>
<th>Graft manipulation</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Italian (Mancardi et al., 2012) 1996–2008</td>
<td>Multicentre case series</td>
<td>74</td>
<td>RRMS n = 33, SPMS n = 41</td>
<td>6.3 (3.5–9.0)</td>
<td>Cy/GF</td>
<td>BEAM/ATG</td>
<td>None</td>
<td>PFS c 66% at 5 years</td>
</tr>
<tr>
<td>CIBMTR/EBMT (Muraro et al., 2013) 1995–2006</td>
<td>Multicentre case series</td>
<td>281</td>
<td>RRMS n = 45, progressive MS n = 236</td>
<td>6.5 (1.5–9.0)</td>
<td>chemo/GF 93%</td>
<td>Intensity: high 19%, intermediate 64%, low 27%</td>
<td>None</td>
<td>PFS c 48% at 5 years</td>
</tr>
<tr>
<td>Swedish (Burman et al., 2014) 2004–2013</td>
<td>Multicentre case series</td>
<td>48</td>
<td>RRMS n = 34, progressive MS n = 7</td>
<td>6.5 (5.0–7.5)</td>
<td>Cy/GF</td>
<td>BEAM/ATG n = 41, Cy/ATG n = 7</td>
<td>None</td>
<td>DFS f 68% at 5 years</td>
</tr>
<tr>
<td>Northwestern (Burt et al., 2015) 2003–2014</td>
<td>Single centre case series</td>
<td>145</td>
<td>RRMS n = 118, SPMS n = 27</td>
<td>2.0 (3.0–5.5)</td>
<td>Cy/GF</td>
<td>Cy/ATG, Alemtuzumab</td>
<td>None</td>
<td>64% improvement of EDSS at 4 years</td>
</tr>
<tr>
<td>ASTIMS (Mancardi et al., 2015) 2004–2009</td>
<td>Multicentre, randomized, open-label, active comparator, phase 2</td>
<td>24</td>
<td>RRMS n = 9, SPMS n = 12</td>
<td>6.0 (5.5–6.5)</td>
<td>Cy/GF</td>
<td>BEAM/ATG</td>
<td>None</td>
<td>79% reduction in new T2 MRI lesions</td>
</tr>
<tr>
<td>HALT-MS (Nash et al., 2015) 2006–2009</td>
<td>Multicentre, single-arm, phase 2</td>
<td>21</td>
<td>RRMS n = 21</td>
<td>4.5 (3.0–5.5)</td>
<td>Steroids/GF</td>
<td>BEAM/ATG</td>
<td>CD34+ selection</td>
<td>EFS i 78% at 3 years</td>
</tr>
<tr>
<td>Russian (Shevchenko et al., 2015) 2005–2011</td>
<td>Single centre case series</td>
<td>99</td>
<td>RRMS n = 43, progressive MS n = 56</td>
<td>3.5 (1.5–8.5)</td>
<td>Steroids/GF</td>
<td>BEAM-like/ATG d</td>
<td>None</td>
<td>EFS i 88% at 3 years</td>
</tr>
<tr>
<td>Canadian (Atkins et al., 2016) 2001–2009</td>
<td>Multicentre, single-arm, phase 2</td>
<td>24</td>
<td>RRMS n = 12, SPMS n = 12</td>
<td>4.3 (3.0–6.0)</td>
<td>Cy/GF</td>
<td>Busulfan, Cy, ATG</td>
<td>CD34+ selection</td>
<td>EFS i 69.6% at 3 years</td>
</tr>
</tbody>
</table>

*EFS included: progression (increase of 0.5 in EDSS score compared to baseline, starting 6 months post-transplant and confirmed 3 months later), relapse (worsening or development of new neurologic sign and corresponding symptom lasting more than 48 h), MRI evidence of disease progression (two or more independent multiple sclerosis-related lesions gadolinium-enhancing or T2-hyperintense lesions on brain MRI performed 1 year or more after transplant) or death.

*Represents interquartile range, the manuscript reported that 15 patients had the EDSS 4.6.

*EFS: clinical and development of new brain lesions by MRI.

*BEAM-like: BEAM with dose reductions of etoposide, cytarabine and melphalan or the combination of carmustine and melphalan.

*EFS from the Russian study was freedom from progression (worsening of at least 0.5 points in EDSS for 2 consecutive assessments 3 months apart) or relapse (acute deterioration of neurologic function more than 24 h without other causes).

*DFS in the Swedish study classified events as relapse, new MRI manifestations, EDSS progression or death.

*Different progressive forms, the majority of participants had secondary progressive multiple sclerosis.

*PFS events included worsening of EDSS or initiation of new disease-modifying agent.

*EFS included clinical relapse, new or enhancing MRI lesion, or sustained EDSS worsening.

*ASTIMS = autologous stem cell transplantation international multiple sclerosis; chemo = chemotherapy-based mobilization; CIBMTR = Center for International Blood and Marrow Transplant Research; DFS = disease-free survival; EBMT = European Blood and Marrow Transplant Group; EFS = event-free survival; GF = growth factors; HALT-MS = Hematopoietic cell autologous transplant for multiple sclerosis; MS = multiple sclerosis; PFS = progression-free survival; progressive MS = combined progressive forms of multiple sclerosis; RRMS = relapsing-remitting multiple sclerosis; SPMS = secondary progressive multiple sclerosis.
front-loaded and may be less expensive overall. However, the procedure is not universally covered by health insurance in the USA, although there is variation across different centres and payors. Approaches in other transplant indications, e.g., myelodysplastic syndromes where Center for Medicare Services established Coverage with Evidence Development, allow coverage of transplant costs with the requirement for systematic and prospective data collection.

**Clinical trials to date**

I/AHSCT has been the most investigated cell-based therapeutic strategy for multiple sclerosis. Recent clinical studies are summarized in Table 1. Most studies were small or single centre case series with different patient populations, therapeutic protocols, and outcome measures. The published experience mostly comprises uncontrolled studies. The one randomized trial (Mancardi et al., 2015) used mitoxantrone, an agent that is now largely less relevant as a comparator.

A recent retrospective analysis indicated that treatment with I/AHSCT achieved NEDA based on relapses, MRI lesion activity, and disability worsening in a higher proportion of multiple sclerosis patients (78–83% at 2 years) than reported in trials of the available DMTs (13–46%) (Sormani et al., 2017). It should be noted that these studies had different patient populations and visit schedules, particularly the frequency of MRI scans, which can have a marked effect on NEDA rate. In addition to potent benefit on clinical measures and MRI lesion activity, I/AHSCT had potent efficacy on normalized whole brain volume loss. Following I/AHSCT there was initial acceleration of, followed by marked slowing after 2 years to levels approximating normal ageing (Roccatagliata et al., 2007; Lee et al., 2017).

Any evaluation of the utility of I/AHSCT needs to assess risk of mortality. In multiple sclerosis, mortality related to the disease may occur, but usually many decades after diagnosis. Thus, any therapy with significant risk of mortality will not readily be accepted. Mortality associated with I/AHSCT has decreased over the past two decades (Sormani et al., 2016). With recent protocols, I/AHSCT is a safer procedure with mortality rates <5% (Muraro et al., 2017), with some trials reporting no mortality (Burt et al., 2015). Risks remain associated with the conditioning intensity, which necessitate careful patient selection (excluding participants with significant recent or chronic infection, liver disease, heart disease, etc.) and adequate supportive care during the 2–3-week aplastic phase. Optimal selection of patients, transplant procedure, timing of transplant, and post-transplant care help minimize the risk of transplant-related mortality. Some delayed adverse events occur late after IAHSC, but they are uncommon. The principal late adverse event is a 9% risk of a secondary autoimmune disorder within 5 years of IAHSC to treat autoimmune disease (Daikeler et al., 2011). Thus, the front-loading of safety issues with IAHSC contrasts with multiple sclerosis DMTs, for which the risk of ongoing therapy accumulates over time related to chronic immune modulation or suppression.

**Key questions/issues and recommendations**

Workshop participants generally agreed on several consensus recommendations.

(i) In aggregate, the available evidence suggests I/AHSCT has substantial and sustained efficacy in suppressing inflammatory disease activity in multiple sclerosis. However, at present, it remains uncertain where the benefit-risk-cost profile of I/AHSCT places it in the treatment for relapsing-remitting multiple sclerosis relative to other available highly effective DMTs.

(ii) Patients most likely to benefit from I/AHSCT are relatively young e.g. 50 years of age or less, with relatively short disease duration e.g. 5 years or less, have active relapsing-remitting multiple sclerosis and accumulating disability but still are ambulatory, and have ongoing disease activity despite DMT. I/AHSCT is unlikely to benefit patients with longstanding progressive multiple sclerosis without recent inflammatory features (clinical relapses or MRI lesion activity).

(iii) We recommend a formal, multicentre, randomized phase 3 trial, comparing I/AHSCT head-to-head versus currently available highly effective therapy(ies) in a defined patient population. Issues concerning the trial design were discussed extensively, but further details still need to be determined (Box 1). Nevertheless, there was a substantial interest in the development of and participation in such a trial.

(iv) If I/AHSCT is performed to treat individual patients in clinical practice, comprehensive safety and efficacy data should be collected, the outcomes submitted to existing registries such as the Autoimmune Disease Working Party of the European Society for Blood and Marrow Transplant (EBMT) (Autoimmune Disease Working Party 2016) and the Autoimmune Diseases and Cellular Therapies Working Committee of the Center for International Blood and Marrow Transplant Research (CIBMTR) (Center for International Blood and Marrow Research 2016), and the results published. However, it is strongly encouraged that efforts be made to enrol such patients into formal clinical trials of I/AHSCT when available.

**Enhanced endogenous cell therapy including mesenchymal stem cells**

**Biological background and rationale**

Many stem cell types have potentially beneficial properties unrelated to trans-differentiation and cell replacement. These ‘non-canonical’ properties, some paracrine, may in some disorders play a greater therapeutic role than conventional cell replacement (Korbling and Estrov, 2003). In neurological disease, neural stem cells, MSCs from bone marrow or...
other sources including adipose tissue, and haematopoietic stem cells have all been shown to have therapeutic potential that depends on such non-canonical properties (Pluchino et al., 2005; Uccelli et al., 2008; Rice et al., 2013). MSCs have attracted the most attention in this regard.

MSCs are present in most (possibly all) tissues (Da Silva Meirelles et al., 2006; Phinney, 2012). Bone marrow contains various non-haematopoietic stem cells, including MSCs, and MSCs are themselves a heterogeneous population (Phinney, 2012). Within the bone marrow, they function to help maintain the haematopoietic stem cell developmental niche (Mendez-Ferrer et al., 2010), but it is increasingly clear they also play a significant systemic role in repair in many tissues. In some diseased or damaged tissues, MSC differentiation into cells of the mesodermal lineage contributes to their putative benefit, for example, in liver and cardiac disease. Despite early reports of trans-differentiation into both neurons and oligodendrocytes (Woodbury et al., 2000), this phenomenon probably does not play a significant role in potential repair-promoting effects of MSCs in the CNS. Rather, their multiple paracrine and other mechanisms of action are more relevant (Box 2), offering the prospect of ameliorating a number of the differing pathological processes contributing to tissue damage in multiple sclerosis through what might be termed ‘enhanced endogenous cell therapy’ (Korbling and Estrov, 2003; Rice and Scolding, 2004).

Some bone marrow cell subpopulations can reside for decades in the human brain after transplantation (Cogle et al., 2004), though it is not yet clear which. There is no such evidence for MSCs specifically and, in fact, some evidence indicates that MSCs do not persist in tissues (von Bahr et al., 2012). Thus, potential therapeutic benefit of MSC transplantation is likely to be self-limited, suggesting repeated administration will be necessary.

### Practical/procedural background

#### Source and cell production

The question of whether MSCs from different tissue sources are identical in all properties is not wholly resolved (Strioga et al., 2012; Li et al., 2015). This uncertainty is partly a consequence of the continuing absence of any unique identifying marker of MSCs. They are consequently defined by a range of properties (Dominici et al., 2006). So, the argument becomes almost circular: do cells with this same defining range of properties have identical additional, non-defining properties? There may be potentially important differences between MSCs derived from different sources, e.g. adipose tissue and bone marrow, and these differences may, in the future, influence the choice of tissue source.

The optimal dose of MSCs in any therapeutic use remains unknown, but a common target is $1-2 \times 10^6$ cells/
**Box 2 Properties of MSCs and bone marrow-derived cells of potential therapeutic value in multiple sclerosis**

- **Remyelination**
  Both MSCs and unseparated, non-expanded bone-marrow-derived cells promote myelin repair following intravenous injection (Sasaki et al., 2001; Akiyama et al., 2002). The mode of action is not clear. Intravenously-delivered bone marrow-derived cells successfully infiltrate the brain and spinal cord, inflamed or otherwise (Devine et al., 2003; Gordon et al., 2010); and they proliferate and migrate towards cytokines expressed in multiple sclerosis lesions (Rice and Scolding, 2010). Stimulation of CNS endogenous neural precursors (Munoz et al., 2005; Bai et al., 2009), and the release of trophic factors for oligodendrocytes might underlie this effect (Pisati et al., 2007).

- **Reduced gliotic scar formation (Li et al., 2005)**
  Gliosis is widely considered to inhibit spontaneous myelin repair.

- **Angiogenesis (Bronckaers et al., 2014)**
  Angiogenesis would also likely enhance tissue repair.

- **Suppression of inflammation, immune modulation**
  Bone marrow-derived cells have pronounced immune-modulating properties (Prockop and Oh, 2012), affecting both innate and adaptive immune systems. Numerous studies have shown both MSCs and mixed populations of bone marrow-derived cells successfully to abrogate experimental autoimmune encephalomyelitis through increasingly well understood immunosuppressive actions (Bai et al., 2009; Morando et al., 2012). Many consider these immune effects sufficiently potent to justify clinical testing in relapsing-remitting multiple sclerosis [MEsenchymal StEm Cells for Multiple Sclerosis (MESEMS)] (Freedman et al., 2010). However, it should be noted that animal and human MSC responses can be differentially modulated in both pro- and anti-inflammatory directions by environmental factors, such as pathogen-associated molecules and cytokines (Darlington et al., 2010; Rozenberg et al., 2016).

- **Neuroprotection**
  MSCs reduce axon loss in various immune-mediated experimental autoimmune encephalomyelitis models (Zhang et al., 2006), but also in non-immune CNS injury, e.g. stroke models (Chen et al., 2001). Neuroprotective mechanisms include the release of superoxide dismutase-3 (Kemp et al., 2010) and of various neurotrophins (GDNF, BDNF, HGF) (Bai et al., 2012). MSCs also promote CNS neuritis outgrowth, and remodelling (Shen et al., 2011).

- **Cell fusion**
  Bone marrow-derived cells fuse with certain differentiated cell types, including neuronal subpopulations, a phenomenon which is increased in local or systemic inflammation or immune activation, and which likely represents a means of ‘rescuing’ damaged cells and restoring them to normal function (Johansson et al., 2008; Kemp et al., 2014). Transferring mitochondria from MSC to damaged cells can also protect tissue (Rice et al., 2010; Prockop, 2012), membrane fusion (likely relating to nanotube formation or exosome transfer) representing the underlying mechanism common to both cell fusion and mitochondrial ‘donation’. Fusion of infiltrating endogenous bone marrow-derived cells with Purkinje cells appears to occur spontaneously in multiple sclerosis (Rice et al., 2010; Kemp et al., 2012).

BDNF = brain-derived neurotrophic factor; GDNF = glial derived neurotrophic factor; HGF = hepatocyte growth factor.

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Karen body weight—a number that makes uses primary MSCs near impossible for clinical use. Therefore, protocols for expanding cells are widely used (Mosna et al., 2010), though it has become clear that cycles of expansion significantly attenuate many reparative and neuroprotective properties. In addition, the typical yield limits repeat dosing. New approaches to expansion therefore continue to be explored (Hoch and Leach, 2014).

Some studies used mixed/unseparated cells (Rice et al., 2010); others administered purified and culture-expanded MSCs (Karussis et al., 2010; Yamout et al., 2010; Bonab et al., 2012; Connick et al., 2012; Cohen et al., 2017). Some authors have studied modified MSCs adapted to express and secrete particular neurotrophins, though less so in multiple sclerosis models. Others have pre-differentiated MSCs—for example, using the classic neural stem cell mitogenic combination of epidermal growth factor and basic fibroblast growth factor, combined with ‘neurosphere’ culture techniques, to produce cells with MSC-derived neural stem cell properties (Harris et al., 2012). Lack of comparative studies of different cell products and of in vitro markers that relate to therapeutic efficacy preclude recommendations on the optimal cell production protocol.

As in all clinical cell therapy endeavours, there is need for rigorous and stringent quality and safety control in cell production with, in the case of artificially expanded cells, assessment of phenotype and karyotype, mutagenesis testing, and microbiological analysis (Dominici et al., 2006; Mosna et al., 2010). This safety aspect represents one significant reason for caution in considering patient requests to purchase treatments from commercial clinics, particularly in countries where medical facilities are arguably less well regulated.

**Route of delivery**

Directly injecting cells into specific lesions would provide little benefit in the diffuse grey and white matter involvement
that characterizes multiple sclerosis. Cell therapy delivered systematically (as with any conventional drug) may have more rationale—and is safer. Most studies of MSCs have adopted intravenous injection (Rice et al., 2010; Odinak et al., 2014; Lublin et al., 2014; Yamout et al., 2012). Following intravenous injection, many cells are trapped in the lungs, but significant numbers still enter the CNS, become widely distributed, and can remain for decades, as shown in experimental models and in human subjects (Cogle et al., 2004). Emerging evidence also suggests potential immune-modulating effects result from the interaction of MSCs and immune cells in the lung (Lee et al., 2009; Odoardi et al., 2012). Intra-arterial (carotid) delivery of bone marrow-derived MSCs has been explored in multiple system atrophy (Lee et al., 2012), but not in multiple sclerosis to date. Concerns about micro-embolization have limited enthusiasm for this approach. Intrathecal delivery also has been tested in multiple sclerosis (Liang et al., 2009; Riordan et al., 2009; Karussis et al., 2010; Yamout et al., 2010). In the absence of a head-to-head comparison study, the optimal route of delivery remains uncertain.

**Clinical results to date**

Various groups have published small studies exploring feasibility and safety of MSC transplantation in multiple sclerosis (summarized in Table 2). These studies involved differing study populations, cell products, and routes of administration. The results generally supported the feasibility and safety of MSC transplantation in multiple sclerosis, as was expected based on studies in other conditions (Lalu et al., 2012), including no evidence of ectopic tissue formation (von Bahr et al., 2012). Transient aseptic meningitis was common with intrathecal delivery (Karussis et al., 2010). Also, there have been case reports of acute disseminated encephalomyelitis after intrathecal MSC injection (Kishk et al., 2013); a glioproliferative spinal cord tumour after intrathecal injection of a combination of mesenchymal, embryonic, and foetal neural stem cells (Berkowitz et al., 2016); and severe visual loss in three patients with age-related macular degeneration after intravitreal injection of adipose tissue-derived stem cells (Kuriyan et al., 2017). Some uncontrolled studies reported preliminary evidence of benefit on clinical, neurophysiological, or imaging outcomes (Rice et al., 2010; Connick et al., 2012; Cohen et al., 2017).

The consensus among workshop participants was that further clinical trials were warranted. Larger, controlled phase 2 studies of both unseparated, non-expanded bone marrow-derived cells (Rice et al., 2015a,b) and purified, culture-expanded MSCs [MESenchymal StEm Cells for Multiple Sclerosis (MESEMS)] (Freedman et al., 2010) are underway.

**Key questions/issues and recommendations**

Workshop participants identified several methodological issues concerning MSC transplantation in multiple sclerosis (Box 3).

**Cell numbers and types**

Cell dose currently is entirely empirical; there is little or no evidence indicating how many cells might be optimal. Similarly, there is no clear evidence whether multiple infusions would be needed, though this appears intuitively likely, and exploratory trials are underway (Rice et al., 2015b). A further issue is the type of cell preparation to be used. Most studies used mixed mononuclear cell preparations or purified culture-expanded MSCs; some investigators studied MSC-derived neural progenitors (Harris et al., 2012). MSCs are much studied experimentally, and there is an attractive rationale in using a purified homogenous cell population (Freedman et al., 2010). However, bone marrow mononuclear preparations include many cell types, and there is good experimental evidence of benefit of such mixed preparations in repairing demyelination (Akiyama et al., 2002) and suppressing inflammation, as well as clinical evidence in patients with stroke and other diseases (Savitz et al., 2011). We do not know which cells among the bone marrow population are the most valuable therapeutically; there is no known benefit from excluding cell populations. Indeed, some evidence points to the superiority in certain experimental situations of using mixed mononuclear preparations over purified MSCs. The former simpler approach requires fewer technical resources and avoids the potential risks of genetic instability (Miura et al., 2006), infection (Uihlin et al., 2014), and altered phenotype that may accompany multiple cell cycling in culture for expansion. At present, it appears reasonable for both approaches to be pursued.

It is unclear whether the underlying biology of multiple sclerosis might affect MSC function. Some studies have demonstrated similar growth in culture, differentiation potential, surface antigen expression, and immunomodulatory properties of MSCs isolated from multiple sclerosis subjects versus non-multiple sclerosis controls (Papadaki et al., 2005; Mazzanti et al., 2008; Mallam et al., 2010; Kassis et al., 2013). Other studies reported notable functional differences (de Oliveira et al., 2015; Redondo et al., 2016; Sarkar et al., 2016), suggesting autologous cell transplantation might not be appropriate. Commercial studies using pooled culture-expanded (heterologous) MSCs in non-multiple sclerosis conditions have, thus far, had disappointing efficacy results. Issues of donor variance, immunogenicity, culture expansion, epigenetic reprogramming, senescence, and (perhaps particularly) cryopreservation and thawing (Francois et al., 2012; Chinnadurai et al., 2014, 2016) may have contributed to these negative results.
Table 2 Published studies of MSC transplantation in multiple sclerosis

<table>
<thead>
<tr>
<th>Reference</th>
<th>Study population* (n)</th>
<th>Post-treatment follow-up (months)</th>
<th>Cell product</th>
<th>Route of administrationb</th>
<th>Efficacy outcomes</th>
<th>Adverse events (number of patients)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bonab et al. (2007)</td>
<td>Progressive MS (10) unresponsive to treatment, EDSS 3.5–6.0</td>
<td>13–26 (mean 19)</td>
<td>Autologous, culture-expanded BM MSCs</td>
<td>IT</td>
<td>EDSS change (n): improved (1) stable (4), worse (5); MRI lesions (n): decrease (1), no change (7), increase (2)</td>
<td>No serious adverse events</td>
</tr>
<tr>
<td>Bonab et al. (2012)</td>
<td>SPMS (23), PRMS (2) unresponsive to treatment, mean EDSS 6.1</td>
<td>12</td>
<td>Autologous, culture-expanded BM MSCs</td>
<td>IT</td>
<td>Discontinued study (n = 3); EDSS change (n): improved (4) stable (12), worse (6); MRI lesion activity (n): none (15), present (6), no data (1)</td>
<td>Low-grade fever (n = 1); nausea, vomiting (2), lower limb weakness (2), headache (3) No serious adverse events</td>
</tr>
<tr>
<td>Cohen et al. (2017)</td>
<td>RRMS (10), SPMS (14); clinical or MRI activity or worsening in the prior year; afferent visual pathway involvement; EDSS 3.5–6.5</td>
<td>6</td>
<td>Autologous, culture-expanded BM MSCs</td>
<td>IV</td>
<td>No benefit on MRI lesion activity; possible benefit on EDSS and whole brain MTR</td>
<td>No serious or severe adverse events</td>
</tr>
<tr>
<td>Connick et al. (2012)</td>
<td>SPMS (10), afferent visual pathway involvement, EDSS 5.5–6.5</td>
<td>5.8–10.2 (mean 7.0)</td>
<td>Autologous, culture-expanded BM MSCs</td>
<td>IV</td>
<td>Improvement in visual acuity and visual evoked response latency, increase in optic nerve area on MRI</td>
<td>Transient post-infusion rash (1), bacterial infection (2) No serious adverse events</td>
</tr>
<tr>
<td>Karussis et al. (2010)</td>
<td>RR or progressive MS (15 total) unresponsive to treatment, EDSS 4.0–8.0</td>
<td>6</td>
<td>Autologous, culture-expanded BM MSCs</td>
<td>IT (+ IV in five)</td>
<td>Improved mean EDSS 6.7 to 5.9, no new enhancing MRI lesions at 6 months</td>
<td>Transient fever (10), headache (10), meningeval irritation and aseptic meningitis (1) No major adverse events</td>
</tr>
<tr>
<td>Li et al. (2014)</td>
<td>RR or SPMS (23), 13 treated versus 10 controls</td>
<td>12</td>
<td>Allogeneic human umbilical cord-derived MSCs</td>
<td>IV three times over 6 weeks, with corticosteroids</td>
<td>EDSS and relapses significantly improved compared to control group</td>
<td>None reported</td>
</tr>
<tr>
<td>Liang et al. (2009)</td>
<td>PPMS (1) unresponsive to treatment, EDSS 8.5</td>
<td>5</td>
<td>Allogeneic human umbilical cord-derived MSCs</td>
<td>IT + IV, with cyclophosphamide</td>
<td>Improved EDSS 8.5 to 5.5, decreased MRI lesion load</td>
<td>None reported</td>
</tr>
<tr>
<td>Llufriu et al. (2014)</td>
<td>RRMS (9) five treated versus four placebo, unresponsive to treatment, EDSS 3.0–6.0</td>
<td>12</td>
<td>Autologous, culture-expanded BM MSCs</td>
<td>IV</td>
<td>Non-significant decrease in cumulative number of enhancing MRI lesions</td>
<td>No serious adverse events</td>
</tr>
<tr>
<td>Lublin et al. (2014)</td>
<td>Treated (12): RRMS (7); SPMS (5) versus placebo (4): RRMS (3), SPMS (1); clinical or MRI activity or worsening in the prior year; EDSS 1.5–6.5</td>
<td>12</td>
<td>Allogeneic human placenta-derived MSCs</td>
<td>IV, one infusion (low dose) or two infusions (high dose)</td>
<td>No significant change in EDSS or enhancing MRI lesions</td>
<td>MS relapse (1), anaphylactoid reaction (1), superficial thrombophlebitis (1), headache (7), infusion site reaction (6) No significant adverse events reported</td>
</tr>
<tr>
<td>Odinak et al. (2011)</td>
<td>MS, course not specified (8)</td>
<td>12</td>
<td>Autologous, culture-expanded BM MSCs</td>
<td>IV</td>
<td>EDSS change (n): improved (6), stable (1), worse (1)</td>
<td>No significant adverse events reported</td>
</tr>
<tr>
<td>Rice et al. (2010)</td>
<td>Progressive MS with recent relapse (6); EDSS 4.5–6.5</td>
<td>12</td>
<td>Autologous, culture-expanded BM MSCs</td>
<td>IV</td>
<td>Multi-modal evoked potential improvement</td>
<td>Transient increase in lower limb spasticity (2), urinary retention (1) No serious adverse events</td>
</tr>
<tr>
<td>Riordan et al. (2009)</td>
<td>RRMS (3), unresponsive to treatment</td>
<td>3–7</td>
<td>Autologous, non-expanded adipose SVF, allogeneic CD34 + cells, allogeneic MSCs</td>
<td>Two IV SVF infusions, multiple IV + IT infusions of CD34 + cells and MSCs</td>
<td>Clinical improvement</td>
<td>No side effects reported</td>
</tr>
</tbody>
</table>

(continued)
**Consensus recommendations**

MSC and related cell therapy is an active area of research. Several phase 2 trials are already underway (Freedman et al., 2010; Rice et al., 2015a), which should clarify whether this approach is a potentially efficacious treatment for multiple sclerosis and in what phase of the disease. Workshop participants agreed it remains important to monitor carefully for long-term adverse effects, perhaps through international registries.

If the concept that underlies MSC therapy proves to be of benefit in diseases like multiple sclerosis, it may be that enhanced endogenous cell therapy will ultimately give way to molecular treatments. If the main beneficial effects of MSC therapy are paracrine, these might be more conveniently reproduced by directly using the principal effectors elaborated by infiltrating cells. The problem, however, is that not all the multiple therapeutic capacities of MSC-related populations are uniformly activated in all disease situations. Rather, infiltrating cells probably ‘sense and react’, with specific pathways triggered in response to the tissue and form of tissue damage (Murphy et al., 2013). This process is likely dynamic, with the profile of administered cells and of those infiltrating tissues evolving with the progress of each individual disease or injury. It may be challenging to reproduce this by administering molecules rather than cells.

### Pharmacological manipulation of endogenous repair mechanisms

#### Biological background and rationale

The traditional approach to develop remyelination-promoting pharmacologic therapies begins with basic studies of myelination and remyelination followed by development of agents that augment these processes. Such studies have identified a sizable number of candidate therapeutics (Kremer et al., 2016). When the agents are novel, e.g. the anti-LINGO-1 monoclonal antibody opicinumab (Mi et al., 2013), they then must go through the standard regulatory approval process of preclinical studies then phase 1–3 clinical trials (Mi et al., 2013). However, a sizable number of already existing medications also may have the ability to promote remyelination (Kremer et al., 2016); ‘repurposing’ these agents could expedite testing and regulatory approval. A complementary molecular approach involves using cultured OPCs or OPC-like iPSCs as the basis for high-throughput screening of libraries of already available drugs for their ability to stimulate remyelination (Deshmukh et al., 2013; Mei et al., 2014; Najm et al., 2015). Molecules identified in the initial screens were further evaluated by increasingly stringent *in vitro* and *in vivo* testing, identifying the muscarinic antagonist benzotroline, the antihistamine clemastine, the imidazole antifungal miconazole, and the topical steroid clobetasol as potential

<table>
<thead>
<tr>
<th>Route of administration</th>
<th>Efficacy outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>IT (lumbar + cisternal)</td>
<td>EDSS change at 12 months</td>
</tr>
<tr>
<td>Autologous, culture-expanded BM MSCs</td>
<td>(n): improved (5), stable (1), worse (1); MRI at 3 months (5/7), enhancing T2 lesions (5/7)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reference</th>
<th>Study population</th>
<th>Cell product</th>
<th>Post-treatment follow-up (months)</th>
<th>Route of administration</th>
<th>Adverse events</th>
<th>Efficacy outcomes</th>
<th>Adverse events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yamout et al. (2010)</td>
<td>SPMS (7); EDSS 4.5–7.5</td>
<td>Autologous, culture-expanded BM MSCs</td>
<td>12</td>
<td>IT (lumbar + cisternal)</td>
<td>Transient encephalopathy with seizures (1), cervical and back pain (1)</td>
<td>No serious adverse events</td>
<td>(n): improved (5), stable (1), worse (1); MRI at 3 months (5/7), enhancing T2 lesions (5/7)</td>
</tr>
</tbody>
</table>

*No control arm unless otherwise noted.

*Single administration and without concomitant multiple sclerosis disease therapy unless otherwise noted.

BM = bone marrow; IT = intrathecal; IV = intravenous; MS = multiple sclerosis; MTR = magnetization transfer ratio; PPMS = primary progressive multiple sclerosis; PRMS = progressive relapsing multiple sclerosis; SPMS = secondary progressive multiple sclerosis; SVF = stromal vascular fraction.

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**Table 2 Continued**

*Reference Study population a (n)*

<table>
<thead>
<tr>
<th>Reference</th>
<th>Study population</th>
<th>Cell product</th>
<th>Post-treatment follow-up (months)</th>
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<td>SPMS (7); EDSS 4.5–7.5</td>
<td>Autologous, culture-expanded BM MSCs</td>
<td>12</td>
<td>IT (lumbar + cisternal)</td>
<td>Transient encephalopathy with seizures (1), cervical and back pain (1)</td>
<td>No serious adverse events</td>
<td>(n): improved (5), stable (1), worse (1); MRI at 3 months (5/7), enhancing T2 lesions (5/7)</td>
</tr>
</tbody>
</table>

*No control arm unless otherwise noted.

*Single administration and without concomitant multiple sclerosis disease therapy unless otherwise noted.

BM = bone marrow; IT = intrathecal; IV = intravenous; MS = multiple sclerosis; MTR = magnetization transfer ratio; PPMS = primary progressive multiple sclerosis; PRMS = progressive relapsing multiple sclerosis; SPMS = secondary progressive multiple sclerosis; SVF = stromal vascular fraction.
candidates for further testing (Deshmukh et al., 2013; Mei et al., 2014; Najm et al., 2015).

Practical/procedural background

Agents identified through the approaches described above are anticipated to have a wide range of mechanisms of action and pharmacological properties. Therefore, the design of proof-of-principle clinical trials in multiple sclerosis will vary according to the agent under study.

Clinical trials to date

A pilot study of clemastine fumarate to promote inherent remyelination showed improvement on visual evoked potentials in participants with multiple sclerosis-related chronic optic neuropathy (Green et al., presented at the 2016 Annual Meeting of the American Academy of Neurology). The RENEW trial of opicinumab in acute optic neuritis demonstrated benefit on visual evoked potential latency recovery in the per-protocol analysis but not in the intention-to-treat analysis or on visual function or optical coherence tomography measures (Cadavid et al., 2017). The SYNERGY trial of opicinumab in relapsing multiple sclerosis did not demonstrate benefit on the primary endpoint, percentage of participants with confirmed improvement on a composite outcome measure comprising EDSS, timed 25-foot walk, 9-hole peg test, and paced auditory serial addition test (Cadavid et al., 2016).

Key questions/issues and recommendations

A number of studies of such agents are underway or planned. The key question is whether medications identified through basic studies of myelination/remyelination or high throughput screening, in fact, promote remyelination in patients with multiple sclerosis and how to demonstrate it. Some of the theoretical problems applying to the potential use of remyelinating cells, as outlined below, also apply—for example, the question of whether degenerated axons can support remyelination.

Oligodendrocyte progenitor cells and induced pluripotent cells

Biological background and rationale

Cell-based remyelinating strategies have long been of interest as a potential therapeutic approach in progressive multiple sclerosis. Glial progenitor cells expressing A2B5 but not polysialylated neural cell adhesion molecule can be isolated from foetal human brain (Windrem et al., 2004), and when injected intracerebrally into hypomyelinating shiverer mice mediate widespread myelination and reversal of the clinical phenotype (Windrem et al., 2008). These cells can be further purified by selecting for expression CD140a and


Box 3 Key issues related to future trials of MSC transplantation in multiple sclerosis

1. Cell product
   - Tissue source: bone marrow versus adipose tissue versus other tissues
   - Mixed/unseparated cells versus purified cultured-expanded cells
   - Cryopreserved and thawed versus unfrozen
   - Autologous versus heterologous

2. Route of delivery: intravenous versus intrathecal versus intra-arterial versus a combination

3. Dose and dosing
   - Cell number
   - Single versus multiple infusions

4. Trial design
   - Appropriate study population
   - Primary trial outcome—should it focus on anti-inflammatory effects or repair?
   - Comparator
   - Allowed concomitant multiple sclerosis DMT(s): how might available multiple sclerosis DMTs affect success/viability of MSC transplantation?
   - Safety monitoring, short and long term
     - Infusion-related toxicity
     - Acute and late infection
     - Ectopic tissue formation
     - Cancer

5. How might underlying multiple sclerosis disease process affect success/viability of MSCs as a treatment approach?
platelet-derived growth factor alpha receptor, which yields the more potent myelinogenic fraction (Sim et al., 2011). Similarly, iPSCs might be used as a source of oligodendrocytes, with the potential for autologous cells to be used (Thiruvalluvan et al., 2016). There are a number of potential therapeutic targets for such cells (Goldman et al., 2012), including genetic dysmyelinating disorders, traumatic brain and spinal cord injury, and acquired inflammatory demyelinating disorders such as multiple sclerosis.

**Practical/procedural background**

Because OPCs are not expected to be capable of trafficking from blood or CSF into the CNS parenchyma, it is assumed that direct injection will be necessary for the cells to gain access to demyelinated lesions in multiple sclerosis, which introduces an additional level of technical and safety concerns. It appears that the cells have the capacity to migrate substantial distances within the CNS (Goldman et al., 2012), so it may be possible to inject the cells into selected locations and still obtain widespread repair.

Another issue is that the current principal source of OPCs is foetal tissue, which provides a limited number of cells, given the finite proliferative capacity of OPCs in culture. Because such cells would be allogeneic, immunosuppression of the recipient is required to prevent rejection. It is reassuring that a previous study demonstrated that corticosteroids, interferon-beta, and azathioprine did not affect OPC proliferation, survival, or migratory capacity (Halfpenny and Scolding, 2003).

For the reasons outlined, generation of OPCs from iPSCs generated from the recipient is an attractive alternative approach. However, some studies of human iPSCs have detected frequent genetic modifications, including aberrant DNA methylation and mutations in genes implicated in cancer (Gore et al., 2011; Hussein et al., 2011; Lister et al., 2011), raising the possibility of aberrant tissue formation or malignant transformation after transplantation. To design cell lines safe for human use, more research is required concerning the mechanisms leading to genetic alterations in iPSCs. As a result, there will be substantial regulatory hurdles prior to human testing of such cells. These issues provide much of the impetus for identifying agents that stimulate remyelination by acting through intrinsic OPCs rather than relying on administration of exogenous cells.

**Clinical trials to date**

A phase 1 trial currently is planned by the New York State Consortium for Cell Therapy to evaluate the feasibility and safety of intracerebral injections of escalating doses of OPCs into multiple locations at a single time point in patients with secondary progressive multiple sclerosis (Goodman, 2016). To prevent transplant rejection, participants will receive tacrolimus and mycophenolate mofetil for 6 months then mycophenolate mofetil alone. Safety studies will include clinical assessment, laboratory studies, and brain MRI.

**Key questions/issues and recommendations**

The planned phase 1 study of OPC transplantation will focus on feasibility and safety as a prelude to proof-of-principle studies evaluating whether administration of exogenous OPCs augments remyelination in multiple sclerosis. Workshop participants supported further exploration of OPC transplantation in multiple sclerosis, but with some reservations (Box 4). Some studies have demonstrated sizable numbers of OPC in some chronically demyelinated lesions (Chang et al., 2002), suggesting that lack of such cells is not the cause of inadequate remyelination in multiple sclerosis. Rather, the lack of factor(s) necessary to support and sustain remyelination, the presence of inhibitory factor(s) in the multiple sclerosis lesion environment, and inability of degenerated axons to support remyelination may be the main obstacles. Thus, administration of exogenous cells may not address the need. Even if the proof-of-principle with exogenous OPCs can be demonstrated with reasonable safety, there are several practical issues that need to be resolved, e.g. the appropriate cell dose and patient population most likely to benefit.

**Ethical considerations**

Cell-based therapies for multiple sclerosis are experimental, and strict adherence to ethical guidelines for human subject research (World Medical Association Declaration of Helsinki) helps preserve patient welfare and the integrity of the research process (Box 5) (Hyun et al., 2008). Specific guidelines for human embryonic stem cell research broadly applicable to cell-based therapies for multiple sclerosis, including the most recent revision of international guidelines in 2016 (International Society for Stem Cell Research 2016; National Research Council and Institute of Medicine of the National Academies; Daley et al., 2016), stress the ethics of procurement, derivation, banking, distribution, and use of cells and tissues, including somatic tissues and human totipotent or pluripotent stem cell lines.

Media attention has resulted in some cases of misrepresentation and exaggeration of therapeutic claims for cell-based therapies for multiple sclerosis and other diseases. In the consent process, patients need to be clearly informed that the cell-based therapy procedure is not 'standard of care'. Background information must include what is known about the procedures they are considering and what the goals are of the study in which they will participate. Close attention must be paid to known safety concerns and the potential for unanticipated adverse events.

The existence of many stem cell clinics around the world has resulted in ‘medical tourism’ by patients who believe they have exhausted other routes of treatment and are
Future directions

Cell-based therapies in multiple sclerosis have been pursued experimentally for at least four decades (Blakemore, 1977), and the past few years have witnessed considerable progress. Each of the cell-based approaches discussed above has begun to enter clinical trials. Much work remains, however. There is no clear consensus about their relative roles, especially in comparison with available DMTs, the specifics of the procedures, or the most appropriate patient population and study design to demonstrate short- and long-term safety and efficacy.

In spite of these uncertainties, there was agreement among workshop participants that I/AHSCT appears to have potent efficacy in relapsing-remitting multiple sclerosis though with significant safety concerns. The principal question is where I/AHSCT should be placed in the overall treatment for relapsing-remitting multiple sclerosis. Other cell-based therapeutic strategies—MSC or OPC/iPSC transplantation, and manipulation of endogenous stem cells—may be more helpful in patients with progressive forms of multiple sclerosis where degenerative mechanisms predominate, but this hypothesis remains to be confirmed. Thus, all forms of cell-based therapy for multiple sclerosis should be considered experimental at this time. There may be rare patients with highly aggressive relapsing-remitting multiple sclerosis who have failed available therapies for whom I/AHSCT may be justified. Other than these patients, cell-based therapy of multiple sclerosis should be pursued only in rigorous clinical trials. In all cases, comprehensive safety and efficacy data should be collected and submitted to existing registries, with the expectation that the results will be published.

It seems clear that the most efficient approach to cell-based therapeutic trials for a relatively uncommon disease with approved, available DMTs like multiple sclerosis, is not through the independent effort of many disconnected clinical centres, but through the development of stable, inclusive networks of investigators involved in a spectrum of cell-based therapies. Such networks can function beyond the organization of a single multicentre clinical trial and can establish protocols; undertake studies; and importantly set up registries to record transplantation protocols and outcomes. The Autoimmune Disease Working Party of the EBMT and the Autoimmune Diseases and Cellular Therapies Working Committee of the CIBMTR (Center for International Blood and Marrow Research, 2016) maintain longstanding registries of patients with autoimmune disorders, including multiple sclerosis, undergoing I/AHSCT. More recently, networks have been established for MSC transplantation trials (MESEMS) (Freedman et al., 2010). Given the experimental status of cell-based therapy, we recommend all patients undergoing these procedures either in trials or in clinical practice are recorded in registries. In addition, important biological questions remain for all forms of cell-based therapy. Therefore, well designed mechanistic studies using validated methods for sample procurement and handling also should be included.

Undertaking clinical trials is a costly enterprise, even without the creation and maintenance of networks and collaborative working groups. It is unlikely that any single
source can meet all funding needs. Collaborative funding networks for such efforts have been created, for example, the International Progressive Multiple Sclerosis Alliance; the New York State Consortium for Stem Cell Therapy for Progressive Multiple Sclerosis; government agencies such as Immune Tolerance Network of the National Institute of Immunology Allergy and Infectious Disease and National Institute of Neurological Disorders and Stroke, the National Institute of Heart Lung and Blood, the National Cancer Institute, all of the United States National Institutes of Health; and others. Public-private funding consortia will likely be needed to raise sufficient funds to undertake studies and to create and maintain networks and registries. While there is documented interest in such support from private foundations, care needs to be taken to avoid confusion between the concepts of ‘care’ and ‘research’ in the absence of public support and independent oversight. The issues of private stem cell clinics, which ‘sell’ research that is supported by patients undergoing treatment, are fraught with ethical and practical concerns.

Given the interest in all forms of cell-based therapies for multiple sclerosis, and the increasing number of observational and randomized studies that are being done and proposed, there will likely be more opportunities than funds available. Prioritization among opportunities will be important for funders as well as investigators, and encouraging creation of research networks will encourage efficiencies for both scientific progress and expenditure of limited funds.

### Concluding remarks

(i) Immunoablation followed by autologous haematopoietic stem cell transplantation appears to have potent and durable efficacy in relapsing-remitting multiple sclerosis though with significant safety concerns. The principal question is where this therapeutic approach should be placed in the overall treatment for relapsing-remitting multiple sclerosis.

(ii) There may be rare patients with highly aggressive relapsing-remitting multiple sclerosis who have failed available therapies for whom IAHSCT may be justified as part of clinical practice. Other than these patients, cell-based therapy of multiple sclerosis should be pursued in clinical trials.

(iii) Cell-based therapy—transplantation, mobilization, and pharmacologic manipulation—may be helpful in patients with progressive forms of multiple sclerosis where
(iv) All forms of cell-based therapy for multiple sclerosis should be considered experimental at this time. When it is pursued, comprehensive safety and efficacy data should be collected and submitted to existing registries, with the expectation that the results will be published. Because important biological questions remain for all forms of cell-based therapy, mechanistic studies should be included.

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**Conflicts of interest**

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