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Intravenous apoptotic spleen cell infusion induces a TGF-beta-dependent regulatory T cell expansion

François Kleinclauss¹⁻⁵, Sylvain Perruche¹⁻⁴, Emeline Masson¹⁻⁴, Marcelo de Carvalho Bittencourt¹⁻⁴, Sabea Biichle¹⁻⁴, Jean-Paul Remy-Martin¹⁻⁴, Christophe Ferrand¹⁻⁴, Mael Martin⁵, Hugues Bittard^{4,5}, Jean-Marc Chalopin^{1,2,4,6}, Estelle Seilles¹⁻⁴, Pierre Tiberghien¹⁻⁴, Philippe Saas^{1-4*}

¹INSERM U645, Besançon, F-25020 France; ²Univ Besançon, Besançon, F-25020 France; ³EFS BFC, Besançon, F-25020 France; ⁴IFR 133, Besançon, F-25000 France; ⁵CHU Besançon, Service d'Urologie, Besançon, F-25000 France; ⁶Service de Néphrologie, Besançon, F-25000 France.

F Kleinclauss and S Perruche contributed equally to this work

MCB Current address: INSERM UMR433, Laboratoire de Virologie-Immunologie, CHRU Fort de France, F-97261, Martinique

*Corresponding author: P Saas, INSERM U645/EA 2284/EFS Bourgogne Franche-Comté, 1 Bd A Fleming, BP1937, F-25020 Besançon, France. Tel: 33 3 81 61 56 15; FAX: 33 3 81 61 56 17; E-mail: philippe.saas@efs.sante.fr

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Abstract

Apoptotic leukocytes are endowed with immunomodulatory properties that can be used to enhance hematopoietic engraftment and prevent graft-versus-host disease. This apoptotic cell-induced tolerogenic effect is mediated by host macrophages and not recipient dendritic cells or donor phagocytes present in the bone marrow graft as evidenced by selective cell depletion and trafficking experiments. Furthermore, apoptotic cell infusion is associated with TGF- β -dependent donor CD4⁺CD25⁺ T cell expansion. Such cells have a regulatory phenotype (CD62L^{high} and intracellular CTLA-4⁺), express high levels of Foxp3 mRNA and exert *ex vivo* suppressive activity through a cell-to-cell contact mechanism. *In vivo* CD25 depletion after apoptotic cell infusion prevents the apoptotic spleen cell-induced beneficial effects on engraftment and graft-versus-host disease occurrence. This highlights the role of regulatory T cells in the tolerogenic effect of apoptotic spleen cell infusion. This novel association between apoptosis and regulatory T cell expansion may also contribute to preventing deleterious autoimmune responses during normal turnover.

Keywords: Transplantation; macrophages; apoptosis; regulatory T cells

Abbreviations: Ab, antibody; APC, allophycocyanin; BM, bone marrow; BMT, bone marrow transplantation; CDC, complement-dependent cytotoxicity; DC, dendritic cells; DT, diphtheria toxin; Foxp3, forkhead-box transcription factor p3; GvHD, graft-versus-host disease; HC, hematopoietic cell; mAb, monoclonal antibody; MLR, mixed leukocyte reaction; PerCP, peridinin chlorophyll-a protein; QRT-PCR, quantitative real time PCR; TBI, total body irradiation; Tr1, T regulatory type 1 cells; Treg, regulatory T cells

Introduction

Immune tolerance is maintained by several mechanisms.¹ In addition to central tolerance, various peripheral mechanisms, including T cell anergy or peripheral T cell deletion, cooperate to prevent unwanted T cell immune responses directed against self antigens.¹ Recently, active suppression by CD4⁺CD25⁺ regulatory T cells (Treg) has been extensively explored as a mechanism involved in limiting auto-immunity^{2,3} as well as a way to induce transplantation tolerance.⁴ Thus, CD4⁺CD25⁺ Treg cells have been shown to prevent acute graft-versus-host disease (GvHD),^{5,6} a frequent complication of allogeneic hematopoietic cell (HC) transplantation. Expression of CD25 is shared by different CD4⁺ Treg subsets including CD4⁺CD25⁺ "suppressive" T cells which act by cell contact-dependent mechanisms,^{3,7} IL-10 producing T regulatory type 1 (Tr1) cells⁸ and TGF- β producing Th3 cells.⁹ Other Treg-associated molecules such as CD62L or CTLA-4 (CD152) are commonly used to identify CD4⁺ Treg cells.^{4,5} Recently, forkhead-box transcription factor p3 (Foxp3, called also scurfine) has emerged as an adequate marker for "natural" CD4⁺CD25⁺ "suppressive" T cells¹⁰⁻¹² as well as other peripherally produced CD4⁺ T cells endowed with regulatory properties.¹³⁻¹⁵ However, the phenotypic characterization as well as suppressive mechanism of CD4⁺ Treg cells may differ, depending on the experimental model used.³

Apoptosis is a physiological process which liberates intracellular proteins, rendering critical the maintenance of self-tolerance. Thus, following normal cellular turnover, billions of apoptotic cells are produced every day without systematically causing autoimmunity. Several peripheral tolerance mechanisms explaining the absence of immune responses against apoptotic cell-derived Ags have been proposed.¹⁶⁻¹⁸ First, professional phagocytes, such as macrophages¹⁹ or certain dendritic cells (DC) subsets,²⁰⁻²³ quickly capture apoptotic bodies, thereby preventing the release of harmful products from dying cells.²⁴ In addition, apoptotic

cell death is frequently associated with an immunomodulatory milieu that may neutralize immune cells present in the environment of dying cells. Such milieu consists mainly of anti-inflammatory cytokines like IL-10 or TGF- β released by macrophages which phagocytose apoptotic cells^{19,25,26} or by circulating monocytes in the absence of phagocytosis.²⁷ Furthermore, some cells like T cells may release TGF- β or IL-10 in the course of their apoptotic process.^{28,29} Although the release of TGF- β or IL-10 during apoptosis has been extensively reported,^{19,25-29} capacities of apoptotic cells to induce a CD4⁺ T cell subset endowed with regulatory properties has not been demonstrated so far.

Allogeneic HC transplantation is characterized by the presence of immunocompetent cells of both host and donor origin and the subsequent alloreactive conflict. Donor graft rejection is mainly mediated by recipient T or NK cells that resist the conditioning regimen. In contrast, donor immune cells present in the HC graft are responsible for inducing GvHD. In some situations, GvHD can be beneficial to the host by limiting leukemia relapse (graft-versus-leukemia effect). Strategies are required to control this alloreactive conflict that follows allogeneic HC transplantation. Physiological mechanisms that maintain immune homeostasis and self-tolerance have been exploited for a long time to induce tolerance to allograft.³⁰ In this way, we used i.v. infusion of apoptotic leukocytes to enhance bone marrow (BM) engraftment across major histocompatibility barriers whatever their origin.³¹ Here, we reported that after infusion, apoptotic spleen cells were engulfed by splenic dendritic cells and macrophages. Depletion of donor phagocytes present in the graft had no effect on apoptotic cell-induced engraftment. Conversely, depletion of host macrophages –but not host dendritic cells– before transplantation prevented apoptotic spleen cell-induced engraftment. Furthermore, apoptotic spleen cell infusion was associated with donor CD4⁺CD25⁺ T cell expansion which depends on TGF- β production. Such cells had a regulatory phenotype (CD62L⁺, intracellular CTLA4⁺)

and expressed high levels of Foxp3 mRNA. *Ex vivo*, these Treg exerted their suppressive activity through a cell-to-cell contact mechanism independently of IL-10 or TGF- β . *In vivo*, these Treg were involved in the protective effect of donor apoptotic spleen cell administration on GvHD occurrence.

RESULTS

The graft-facilitating effect of apoptotic spleen cell infusion requires host macrophages but not donor phagocytes present in the bone marrow graft.

Apoptotic cells are quickly removed by macrophages^{19,26} or some DC subsets.²⁰⁻²³ To examine which cell populations would engulf apoptotic cells, recipients were given donor fluorescent-labeled apoptotic spleen cells in addition to the BM graft. At various times post-BMT (30, 45 min, 1, 2, 4 and 8 h), the spleen, liver and lungs were analyzed to determine where and by which phagocytes apoptotic cells had been engulfed. Analysis of time kinetics revealed that apoptotic spleen cells were quickly removed mainly by splenic phagocytes, since there was no detectable fluorescent signal in the lung or in the liver at any time points after infusion (data not shown). Flow cytometric analysis indicated that splenic DC as well as macrophages were involved in apoptotic cell uptake (**Figure 1a**). A higher proportion of labeled phagocytes was observed 45 min after infusion, while no signal could be detected in the spleen tested 4 h after infusion (**Figure 1a**). Phagocytes involved in apoptotic spleen cell uptake may be resident host splenic phagocytes and/or phagocytes present in donor BM graft that migrate to the spleen after infusion. To evaluate the involvement of donor phagocytes, an enriched Sca-1⁺ stem cell graft (3×10^5 cells) was used instead of a total BM graft. Despite significant depletion of CD11c⁺ cells ($83 \pm 8\%$) and F4/80⁺ cells ($95 \pm 9\%$) after Sca-1⁺ cell enrichment, donor HC engraftment was conserved (**Figure 1b**). This suggests that donor phagocytes are not required for the graft facilitating effect of apoptotic spleen cells.

To deplete resident host phagocytes, liposomes loaded with clodronate^{32, 33} were infused before BMT. Pretreatment of mice with clodronate-loaded liposomes reduced significantly both the number of splenic CD11b⁺ macrophages and apoptotic cell-induced donor BM engraftment (**Figure 1c**). As previously described,³³ we observed that not all splenic DC subsets were depleted by clodronate-loaded liposome infusion due to their anatomic location

(**Supplementary Figure 1** online). To further explore the role of host DC in the graft-facilitating effect of apoptotic cells, a transgenic mouse model for *in vivo* DC ablation³⁴ was used. Administration of diphtheria toxin (DT) in such recipient transgenic mice allowed splenic DC depletion for 48 h (**Figure 1d** and ref.34). Despite significant depletion of eGFP⁺CD11c⁺ DC at the time of BMT, the graft-facilitating effect of apoptotic cells was maintained (**Figure 1d**). This suggests that host DC are not critical for the graft-facilitating effect induced by apoptotic spleen cell infusion. Altogether, these results show that recipient splenic phagocytes and in particular macrophages are involved in the graft-facilitating effect of i.v. apoptotic cell infusion.

Intravenous apoptotic spleen cell infusion leads to the TGF- β dependent expansion of CD4⁺CD25⁺ regulatory T cells.

We recently reported that i.v. administration of apoptotic spleen cells, simultaneously with BM grafts, favored engraftment via a TGF- β -dependent mechanism.³⁵ Because TGF- β can be implicated in the generation of Treg sub-populations^{9,13-15} and as fluorescent apoptotic bodies within splenic phagocytes could be found (**Figure 1a**), we first analyzed the spleen for the presence of CD4⁺CD25⁺ T cells at week 7-9 post-BMT. Analysis of splenic T cell populations in mice given apoptotic cells revealed a CD4⁺CD25⁺ T cell increase in engrafted versus non-engrafted recipients ($8.8 \pm 0.6\%$ vs. $3.9 \pm 0.4\%$, mean $\pm$ SEM, 10 mice per group, $P < 0.01$, **Figure 2a**). All these recipient mice exhibited a similar splenic cellularity (between $70\text{-}100 \times 10^6$ cells). Expansion of CD4⁺CD25⁺ T cells was restricted to engrafted mice and specific to apoptotic cell infusion, since no such increase was observed in recipient mice engrafting after infusion of a higher number of BM cells (3×10^6 BM cells, $1.0 \pm 0.2\%$, $n = 8$, $P < 0.05$) or after an increased conditioning regimen (total body irradiation, TBI dose: 7 Gy, $1.5 \pm 0.2\%$, $n = 5$, $P < 0.05$) in the absence of apoptotic cells (**Figure 2a**). Such CD4⁺CD25⁺ T cell increase

–observed 7-9 weeks after apoptotic cell infusion– was not systematically found in the blood nor in other organs tested, including BM, cervical as well as inguinal lymph nodes (data not shown). To determine the role of TGF- β in this apoptotic cell-induced increase, CD4⁺CD25⁺ T cells were analyzed at week 7-9 after BMT and TGF- β neutralization. Mice treated with anti-TGF- β antibody (Ab) did not exhibit any increase in splenic CD4⁺CD25⁺ T cells (**Figure 2b**). In contrast, mice given irrelevant Ab plus apoptotic cells had similar splenic CD4⁺CD25⁺ T cell levels as mice receiving apoptotic cells (**Figure 2b**). TGF- β neutralizing effect could be also observed in peripheral blood (62 ± 7 CD4⁺CD25⁺ T cells/ μ L in anti-TGF- β Ab treated mice vs 288 ± 46 cells/ μ L in control Ab-treated mice; $P < 0.01$). Overall, this suggests that TGF- β production is involved in apoptotic cell-induced CD4⁺CD25⁺ T cell increase.

Further phenotypic and functional characterization of splenic CD4⁺CD25⁺ T cells detected in mice given apoptotic spleen cells was performed to know whether such cells displayed regulatory functions. The CD4⁺CD25⁺ T cells present in engrafted mice were of donor origin; they presented a regulatory T cell-like phenotype (CD45RB^{low}CD62L^{high} intracellular CTLA-4^{high}) and expressed high levels of Foxp3 mRNA (**Figure 3a-b**). In contrast, CD4⁺CD25⁺ T cells found in non-engrafted mice exhibited a phenotype rather consistent with an activated T cell phenotype (intracellular CTLA-4^{low}, CD62L^{low}) and were, as expected, of host origin (**Figure 3a**). Purified CD4⁺CD25⁺ T cells from non-engrafted mice expressed low levels of Foxp3 mRNA (**Figure 3b**). Increase of splenic CD4⁺CD25⁺ T cells 7-9 weeks after apoptotic cell infusion was confirmed by direct quantification of FoxP3 mRNA in recipient whole spleen. A 9-fold increase of FoxP3 mRNA expression was detected at week 7-9 after BMT in mice given apoptotic cells plus BM in comparison to mice given BM alone (**Figure 3c**).

Finally, CD4⁺CD25⁺ T cells were functionally characterized in *in vitro* assays. CD25 depletion restored allogeneic proliferation of splenic CD4⁺ T cells from engrafted mice that had received apoptotic spleen cells, whereas CD25 depletion did not affect the proliferation of

splenic CD4⁺ T cells from non-engrafted mice (**Figure 3d**). In addition, suppressive assays with FACS-sorted CD4⁺CD25⁺ T cells demonstrated that apoptotic cell-induced CD4⁺CD25⁺ T cells exerted their suppressive activity through cell contact-dependent mechanisms. Their suppressive activity could only be inhibited by adding a transwell but not by IL-10, TGF- β , or IL-10 and TGF- β neutralization (**Figure 3e**). These results show that simultaneous apoptotic spleen cell and BM infusion induced a TGF- β -dependent splenic expansion of CD62L^{high}CD4⁺CD25⁺ T cells endowed with regulatory properties at week 7-9 after BMT.

Host macrophage but not dendritic cell depletion is critical for the induction of splenic CD62L⁺CD4⁺CD25⁺ T cells after apoptotic spleen cell infusion.

We then considered which host cells phagocytosing apoptotic cells (macrophages and/or DC) were responsible for splenic CD62L^{high}CD4⁺CD25⁺ T cell induction. Effects of DC depletion at time of transplantation were analyzed in CD11c/DTR/eGFP transgenic recipient. No significant modification of CD62L^{high}CD4⁺CD25⁺ T cell population was observed when DC were depleted at time of transplantation in comparison to non-CD11c depleted transgenic mice, even after apoptotic spleen cell infusion (**Figure 4**). Clodronate-liposome infusion at the time of BMT and apoptotic cell infusion induced the failure of both BM engraftment and donor CD4⁺CD25⁺ T cell expansion (data not shown). It was thus difficult to know whether donor CD4⁺CD25⁺ T cells participated to BM engraftment or whether donor CD62L⁺CD4⁺CD25⁺ T cell increase was related to BM engraftment. To answer to this question, splenic CD62L^{high}CD4⁺CD25⁺ T cells were analyzed by cytometry at different early time points after BMT and macrophage depletion (using clodronate-loaded liposome). This phenotype (CD62L⁺CD4⁺CD25⁺) was chosen since we showed that cells with such phenotype express high levels of Foxp3 mRNA (**Figure 3b**) and exert suppressive activity (**Figure 3d-e**). Early after apoptotic spleen cell infusion (day 6 and day 8 after BMT), a significant

increase of CD62L⁺CD4⁺CD25⁺ T cells was observed in the spleen (**Figure 5a**). This increase was not found in irradiated mice (data not shown), in mice receiving BM alone as well as in mice pretreated with clodronate-loaded liposomes before apoptotic spleen cell and BM infusion (**Figure 5a**). This shows that macrophage depletion prevents apoptotic spleen cell-induced CD62L⁺CD4⁺CD25⁺ T cell increase. In addition, these experiments showed that increase of splenic CD62L⁺CD4⁺CD25⁺ T cells was detected early in all mice receiving apoptotic cells independently of whether they engrafted or not and that this increase implicated both donor and recipient CD62L⁺CD25⁺CD4⁺ T cells (**Figure 5b**). This suggests that the CD62L⁺CD4⁺CD25⁺ T cell increase is independent of BM engraftment and that these cells are induced peripherally after apoptotic cell infusion in the presence of recipient macrophages.

***In vivo* CD25 depletion after donor apoptotic spleen cell infusion limits the graft facilitating effect of apoptotic cells.**

To determine the role of splenic CD62L⁺CD4⁺CD25⁺ T cell expansion after apoptotic spleen cell infusion, anti-CD25 monoclonal antibody (mAb) was infused at day 0 and day 3 after BMT and engraftment was evaluated at week 7 post-BMT. Despite a significant reduction of peripheral blood CD4⁺CD25⁺ T cells one week after BMT (227 ± 25 cells/ μ L in irrelevant mAb treated mice vs. 12 ± 3 cells/ μ L in CD25 treated mice), the administration of anti-CD25 mAb did not significantly alter the proportion of engrafted mice 7-9 weeks post-BMT (50% vs. 42% in mice having received irrelevant mAb, **Figure 6**). However, CD25 depletion significantly decreased the levels of circulating donor-derived cells in engrafted mice at time of engraftment analysis ($24.8 \pm 6.4\%$ donor cells after anti-CD25 mAb administration vs. $72 \pm 15\%$ after control mAb treatment, $P < 0.05$; **Figure 6**). This result was not surprising since CD25 is not a specific marker of Treg and is expressed by activated T cells.⁴ Thus, anti-CD25

mAb might deplete both apoptotic cell-induced recipient and donor-derived Treg as well as host activated T cells that limit engraftment. This latter effect could favor donor engraftment explaining why similar proportions of engrafted mice were found after CD25 depletion. Altogether with kinetic studies showing an early increase of CD62L⁺CD4⁺CD25⁺ T cells after apoptotic cell infusion, these *in vivo* results suggest that CD62L⁺CD4⁺CD25⁺ T cells are involved in the graft facilitating effect observed after apoptotic spleen cell infusion.

Regulatory T cell expansion is involved in the protective effect of donor apoptotic spleen cell administration on graft-versus-host disease occurrence

Apoptotic spleen cell-induced Treg expansion may also be implicated in prevention of GvHD. We have therefore studied the effects of donor apoptotic spleen cell infusion in an experimental model of GvHD. BALB/c recipient mice were lethally irradiated and the following day received a graft containing donor BM cells plus viable donor splenic T cells (to induce GvHD) with or without apoptotic spleen cells from the BM donor origin. Apoptotic cell infusion significantly delayed the onset of lethal GvHD in a dose-dependent manner (**Figure 7a-b**). We then addressed whether donor CD4⁺ CD25⁺ T cells expansion was involved in this delayed GvHD lethality observed after donor apoptotic spleen cell infusion. Depleting anti-CD25 mAb was administrated at days 3 and 6 post-BMT. This treatment abolished completely the protective effect of donor apoptotic cell infusion on GvHD (**Figure 7c**). Overall, these data strongly suggest that donor apoptotic spleen cell infusion induces the expansion of donor-derived CD4⁺ CD25⁺ Treg minimizing anti-recipient immune responses involved in GvHD lethality.

Discussion

New therapeutic approaches are required to modulate alloreactivity in HC transplantation. We recently described an alternative cell-based therapy using i.v. apoptotic leukocyte infusion to favor BM engraftment across MHC barriers.^{31,35} We have previously shown that the apoptotic feature only and not the cell origin is implicated in favoring BM engraftment.³¹ Here, we provide evidence that i.v. infused apoptotic spleen cells were quickly captured by host splenic macrophages and DC. Donor phagocytes present in the BM graft were not implicated in the graft facilitating effect of apoptotic spleen cell infusion. In contrast, depletion of host macrophages –but not host dendritic cells– before transplantation prevented apoptotic cell-induced engraftment. Furthermore, apoptotic spleen cell infusion was associated with donor Treg expansion. *Ex vivo*, these Treg exerted their suppressive activity through a cell-to-cell contact mechanism independently of IL-10 or TGF- β . Both host macrophages and TGF- β production were implicated in this splenic Treg expansion. *In vivo* CD25-depletion after donor apoptotic spleen cell infusion reduced the rate of donor-derived cells and prevented the protective effect of donor apoptotic cell administration on GvHD occurrence. Altogether, these *in vivo* results confirm that Treg induced by the simultaneous infusion of donor apoptotic spleen cells and allogeneic grafts are involved in the immunomodulatory effects of such apoptotic cells on alloreactivity.

Apoptotic cells are endowed with immunomodulatory properties.^{16,17} Macrophages involved in apoptotic cell capture have been described to release TGF- β both *in vitro*¹⁹ and *in vivo*.²⁶ A previous *in vitro* study reported that TGF- β was specifically released by macrophages ingesting apoptotic cells but not during any other type of phagocytosis.¹⁹ TGF- β production is due mainly to the ligation of phosphatidylserines exposed on apoptotic cells to their receptor expressed on macrophages.³⁶ This immunomodulatory milieu created by macrophages

participated in the neutralization of unwanted immune responses against apoptotic cell derived Ag.^{16,26} This may explain why autoimmunity is controlled although billions of cells die during physiological turnover. Moreover, we have reported the absence of autoimmunity after long-term follow-up of mice that had received a single infusion of apoptotic spleen cells simultaneously with their BM grafts.³⁷ TGF- β was reported by several groups to induce CD4⁺CD25⁺ T cells endowed with regulatory functions.¹³⁻¹⁵ Several CD4⁺CD25⁺ T cell subsets have been described to exert regulatory functions.²⁻⁴ Sagakuchi's group first demonstrated that CD4⁺ T cells expressing CD25 molecules controlled autoimmunity in naive mice.² Here, we strongly suggest a direct link between macrophages, apoptotic spleen cell uptake, TGF- β and Treg-like cell expansion. This Treg induction after massive apoptotic primary tissue cell death –that was mimicked in our model by i.v. infusion of five millions of apoptotic spleen cells– may constitute an additional mechanism that takes over from TGF- β secretion to maintain homeostasis. Since TGF- β activation from TGF- β latent complex is known to be tightly regulated and lead to a transient effect restricted to neighbor cells,³⁸ Treg expansion after massive apoptotic cell death may be responsible for long-term autoimmunity control (either locally or in other sites). Interestingly, induction of Treg cells in the spleen after random blood product transfusion has been previously reported³⁹ and non-specific immunomodulatory effects of preoperative blood product transfusion has been proposed to be related to the presence of apoptotic leukocytes present in stored blood products.^{16,40,41} The immunomodulatory role of apoptotic leukocytes can be also extended to the prevention of allo-immune responses. Sun et al. have recently reported that i.v. infusion of donor apoptotic spleen cells prolongs heart allograft survival. Interestingly, these authors demonstrated that this effect required phagocytosis by host cells.⁴² We reported that apoptotic spleen cell infusion with an allogeneic graft prevented anti-BM donor allo-immunization even in mice rejecting their grafts.³⁵ Treg expansion after apoptotic cell infusion could be beneficial for

engraftment as well as to the host (*i.e.*, absence of anti-donor immunization or GvHD control).

Dendritic cell subsets have also been implicated in apoptotic cell uptake^{17,20-23} and subsequent T cell cross-tolerization.²⁰⁻²² In our model, we found fluorescent apoptotic bodies in splenic DC, suggesting that apoptotic cell-derived Ag can also be processed by some DC subsets. However, selective DC depletion did not significantly affect either the graft-facilitating effect or splenic Treg expansion after apoptotic spleen cell infusion. Macrophages were thus sufficient to uptake apoptotic cells and possibly released TGF- β after phagocytosis.^{19,26} Macrophages were more efficient than immature DC to uptake apoptotic cells⁴³ and were found in higher numbers than DC in the spleen. Macrophages may create an immunomodulatory milieu that neutralizes DC Ag-presenting functions. TGF- β has been reported to inhibit the ability of DC to present antigen, stimulate IFN- γ production by T cells, and migrate to draining lymph nodes.⁴⁴ Our model made it possible to determine *in vivo* the respective implications of macrophages and DC after massive apoptotic leukocyte death in an inflammatory situation (*i.e.*, after TBI): macrophages appear as the key players. This sustains the results of Sun *et al.*⁴²

The thymus and the periphery (*i.e.*, where regulation takes place) are both involved in generating Treg. Regulatory T cells induced by apoptotic cell infusion can be generated from a conversion of peripheral naive CD4⁺ T cells into a regulatory phenotype or by an increased production of natural suppressive T cells after engraftment. In our model, several arguments are in favor of the first hypothesis: preferential expansion in the spleen (where fluorescent apoptotic bodies were found), early induction of both donor and recipient populations (as attested by kinetic studies) and TGF- β dependency. Regulatory CD4⁺ T cells induced by *in*

vitro TGF- β exposure arise from "conventional" naive CD4⁺CD25⁻ T cell precursors.¹³⁻¹⁵

They acquire Foxp3 mRNA expression and exert their suppressive activity mainly through TGF- β .¹³⁻¹⁵ In our study, despite TGF- β dependency of Treg induction, such cells induced after apoptotic cell infusion expressed high levels of Foxp3 mRNA and exerted *ex vivo* suppressive activities mainly through a cell contact-dependent activity. However, we cannot exclude that the observed Treg exert their activity through membrane-bound TGF- β .

Membrane TGF neutralization with mAb is indeed not easy to perform.⁷ Human and murine Treg generated in the periphery from naive CD25⁻CD4⁺ T cells can exert suppression through a cell-to-cell contact dependent and cytokine-independent mechanism.⁴⁵⁻⁴⁷ Such findings suggest that apoptotic cell-induced Treg that exert cell-to-cell suppression are generated peripherally from CD4⁺ T cells in the presence of TGF- β . "Spontaneous" conversion of CD4⁺CD25⁻ T cells into CD62L⁺ Foxp3 mRNA⁺ Treg after *in vivo* transfer in syngeneic irradiated recipient has been recently reported.⁴⁵ Thus, *in vivo* administration of apoptotic cells at time of infusion of CD4⁺ T cells may increase the conversion of such cells into Treg.

Increased BM engraftment linked to Treg induction has only been recently reported.⁴⁸⁻⁵⁰ For example, CD8⁺TCR⁻ facilitating cells, derived from BM, induced regulatory T cell genes (including Foxp3) 28 days after transplantation.⁴⁸ This was observed at the time of full donor engraftment suggesting that these putative CD4⁺CD25⁺ Treg cells were of donor origin. In this study, up-regulation of regulatory T cell genes was associated with the absence of GvHD despite donor effector cell administration.⁴⁸ All these data including those on the prevention of GvHD⁵⁻⁶ and our findings highlight the *in vivo* donor Treg induction/expansion as a promising approach to prevent the deleterious alloreactivity after HC transplantation.

In conclusion, apoptotic cell infusion enhances BM engraftment by a TGF- β -dependent mechanism that leads to Treg expansion. For the first time to our knowledge, a link between apoptotic cells and Treg expansion is reported. This could be an additional mechanism to immunomodulatory cytokine production^{19,25-29} or cross-tolerization²⁰⁻²² to prevent deleterious responses against dying cells during normal turnover. We propose to take advantage of this physiological mechanism that maintains self-tolerance to improve HC transplantation outcomes.

MATERIALS AND METHODS

Mice

Specific pathogen-free 5- to 6-week old male FVB (H-2^q), C57BL/6 (H-2^b) and BALB/c (H-2^d) mice (Janvier, Genest-St-Isle, France) were kept in quarantine for at least one week before BM transplantation (BMT). CD11c/DTR/eGFP transgenic mice from a BALB/c background (kindly provided by S. Jung, The Weizmann Institute of Science, Rehovot, Israel) were bred in our animal facility. This transgenic model allows short-term ablation of DC *in vivo* after administration of diphtheria toxin (DT, 100 ng per mouse, Sigma, Saint Quentin Fallavier, France) without affecting macrophages.³⁴ Mice were given *ad libitum* access to food and water. Neomycin sulfate (1.1 g/L, Demavac, Longvic, France) was added to their drinking water as of d-1 of BMT to reduce the risk of infection. Experiments were performed according to institutional guidelines.

Antibodies

The following mAb were used (all obtained from BD PharMingen, San Diego, CA, except when stated): FITC-labeled anti-H-2^q (KH114, mouse IgG2a), CD8 (53-6.7, rat IgG2a), CD11c (HL3, Armenian hamster IgG), CD19 (1D3, rat IgG2a), CD25 (7D4, rat IgM), CD45RB/B220 (RA3-6B2, rat IgG2a), Sca-1 (D7, Rat IgG2a), PE-labeled anti-I-A^b (M5/114.15.2, rat IgG2a, reacts also with I-A^d, I-E^d, I-E^k and I-A^q), H-2^d (SF1-1.1, mouse IgG2a), CD25 (3C7, rat IgG1 or PC61, rat IgG1), CD62L (MEL-14, rat IgG2a), CD117 (2B8, rat IgG2b), CD152 (UC10-4F10-11, Armenian hamster IgG), PE-cyanin 5-labelled F4/80 (A3-1, rat IgG2b, Serotec, Oxford, UK), peridinin chlorophyll-a protein (PerCP)-conjugated anti-CD4 (RM4-5, rat IgG2a), anti-CD3 (145-2C11, hamster IgG1), PerCP cyanin 5.5-conjugated anti-H-2^d (SF1-1.1), CD11b (M1/70, rat IgG2b) and allophycocyanin (APC) conjugated-anti-CD3 (145-2C11). Azide-free low endotoxin purified anti-CD25 (3C7, rat

IgG2b or PC61, rat IgG1) or control (irrelevant) Abs (BD PharMingen) and anti-pan TGF- β (rabbit IgGs) or rabbit IgGs (Sigma) were used *in vivo*.

Cell preparation

Donor BM cells from FVB or C57BL/6 mice and splenocytes from BALB/c, C57BL/6 or FVB mice were prepared as described.^{31,35} After isolation procedures, cell viability was always greater than 90% by Trypan Blue (Sigma) dye exclusion. Sca-1⁺ cell-enriched grafts were obtained by immunomagnetic cell sorting (Miltenyi Biotec, Paris, France) from C57BL/6 BM cells according to the manufacturer's instructions. Purity assessed by Sca-1 mAb staining was > 80% and donor BM phagocyte depletion assessed by CD11c and F4/80 mAb staining was > 83%. Splenocyte apoptosis was induced by a 40-Gray dose of γ -irradiation 6 h before infusion to allow apoptotic changes to occur.³¹ Apoptosis was confirmed by FITC-conjugated Annexin-V (Beckman Coulter Immunotech, Marseille, France) and flow cytometry as well as Hoechst 33342 (Molecular Probes, Eugene, OR) staining and UV microscopy. Absence of secondary necrosis was documented using Trypan Blue staining just before infusion. At time of infusion, spleen cells were mainly early-stage apoptotic cells (70-85% of cells were Annexin-V positive and propidium iodide negative; less than 10% of cells were propidium iodide positive).³¹ Splenic CD62L⁺CD4⁺CD25⁺ T cells were sorted using an EPICS ALTRA cell sorter (Beckman Coulter Immunotech). The purity achieved was >95% and staining these cells did not alter their suppressive function. These purified CD4⁺CD25⁺ T cells were used for *in vitro* assays and RNA extraction for quantitative real time PCR (QRT-PCR).

Bone marrow transplantation

BALB/c recipients were exposed to a sublethal single dose (6 Gy at a rate of 2.7 Gy/min) of TBI 16 h before BMT. After, they were given a single i.v. infusion, via a caudal vein, containing a limited number of FVB or C57BL/6 BM cells (10^6) or Sca-1⁺ cell-enriched graft (10^5) alone or with apoptotic splenocytes (5×10^6) of various origins (recipient, donor or third-party mice). Both hematopoietic grafts and conditioning regimens were defined to favor autologous reconstitution and not engraftment.³¹ Preliminary experiments indicated that a minimum of 10^6 apoptotic spleen cells were required to favor engraftment. The number of apoptotic spleen cells used exceeds this minimum number of cells by a factor of 5. In these conditions (i.e., i.v. infusion of 5×10^6 early-stage apoptotic spleen cells simultaneously with BM grafts), no autoimmunity was observed.³⁷ To study the effects of donor apoptotic cell infusion on the prevention of acute GvHD, we used a lethal dose of TBI (8 Gy) and a higher number of donor BM cells (10^7) as well as donor viable splenic T cells (3×10^6 to trigger GvHD).⁵¹ Increasing numbers of donor apoptotic spleen cells (2×10^6 , 2×10^7 or 10^8) was infused. No immunosuppressive agents were given at any time.

Antibody treatment

Mice were given 150 µg anti-pan TGF-β Ab or rabbit IgGs by tail vein injection on d0 (simultaneously with the graft) and on day 3.³⁵ CD25 cells were depleted by anti-CD25 mAb infusion (8.5 mg/kg or 250 µg/mouse) on day 0 and day 3. Treatment efficiency was confirmed by a significant decrease in circulating CD4⁺CD25⁺ T cells (12 ± 3 cells/µL, $n=3$) as compared to control mAb-treated mice (227 ± 25 cells/µL, $n=3$, $P<0.01$, Student t test).

Host phagocyte depletion

Host phagocyte depletion was performed using clodronate-loaded liposome administration. Liposome preparation and i.v. infusion were performed as described.^{32,33} Briefly, liposomes

consisting of phosphatidyl choline and cholesterol (Sigma) in 6:1 molar ratio were resuspended in PBS and injected via the tail vein (final volume of 0.2 ml containing about 2 mg of clodronate-loaded liposomes). The day after, mice were irradiated and grafted as described above. Host phagocyte depletion was controlled 20 h after treatment, on two treated mice in each experiment, by immunohistochemistry and cytometry analysis. Spleens were removed, cut (5- μ m sections), mounted on microscope slides and air dried for staining. After endogenous phosphatase quenching by levamisole solution (DakoCytomation, Glostrup, Denmark) and nonspecific site blocking, sections were stained with purified CD11b (M1/70), CD11c (HL3) or control Ab (BD PharMingen) and revealed by biotinylated-conjugated goat anti-rat or anti-Armenian hamster Ab (Jackson ImmunoResearch, West Grove, PA) followed by a streptavidin/alkaline phosphatase complex (DakoCytomation). Then, a solution of fuchsin substrate chromogen (DakoCytomation) was added. Hematoxylin was used as a counterstain.

Bone marrow engraftment

Detection of engraftment was performed by flow cytometry^{31,35} using H-2 specific mAb on peripheral blood cells and at week 7 or 9 post-BMT on splenic cells. Analysis was performed with a FACSCaliburTM (BD Biosciences, San Jose, CA) using CellQuest® software (Becton Dickinson) or a CyAn LXTM (DakoCytomation) using Summit® software (DakoCytomation). Recipients were considered as engrafted when they presented at least 15% of cells expressing BM donor H-2.³¹

Tracking of fluorescent apoptotic cells

Apoptotic cells (5×10^6) were labeled using either green PKH67 dye (Sigma) or 5,6-carboxyfluorescein diacetate succinimidyl ester⁵² (CFSE, Molecular Probes, Eugene, OR)

before apoptosis induction according to the manufacturer's instructions. After staining and induction of apoptosis (40 Gy), fluorescent-labeled apoptotic cells were transplanted as previously described with the BM graft in 6-Gy-irradiated recipients. After 30, 45 min, 1, 2, 4 and 8 hrs, mice were CO₂-euthanized; spleen, liver and lungs were harvested to perform fluorescent-labeled apoptotic cell tracking. Cells from each organ were stained using PE-conjugated anti-CD11c and PE-cyanin 5-conjugated anti-F4/80 mAb and analyzed by cytometry.

Phenotypic analysis of T-cell subsets

T-cell subsets from blood, spleen, thymus, BM and LN were analyzed after BMT using specific mAb staining and cytometry. For intracytoplasmic staining, cells were stained with CD3, CD4 and CD25 mAb, fixed in 0.25% paraformaldehyde (Sigma) in PBS and permeabilized in saponin solution (Sigma) prior to staining with CD152 mAb. Absolute counts of circulating lymphocyte subsets were determined using a single-platform approach based on cytometry and tubes containing a defined number of microbeads (TruCOUNT®, BD Biosciences).⁵³

***Ex vivo* functional analysis of CD4⁺CD25⁺ T cells**

Functional characterization of CD4⁺CD25⁺ T cells was performed using two mixed leukocyte reaction (MLR) assays due to limited material and to avoid pooling spleens from separate experimented mice. In the first assay, we depleted CD25⁺ cells among CD4⁺ T cells using complement-dependent cytotoxicity (CDC) and compared CD25-depleted vs non-depleted splenic CD4⁺ T cell proliferation after allogeneic stimulation. In the second assay, we added FACS-sorted splenic CD4⁺CD25⁺ T cells to MLR assays. Spleens from naive FVB (donor origin) or C57BL/6 (third-party origin) mice were 40-Gy irradiated and used as stimulator

cells in both assays. In the first assay, splenic CD4⁺ T cells from BMT recipients (isolated at week 7 post-BMT) were used as responder cells and cultured for 2 h in complete medium containing DMEM supplemented with 10% of heat-inactivated FCS (BioWhittaker, Verviers, Belgium), 5 x 10⁻⁵ M 2-ME, 2 mM L-glutamine, 100 IU/ml penicillin, and 100 µg/ml streptomycin (Sigma). Non-adherent responder cells were washed and incubated for 20 min with purified either anti-CD25 mAb (3C7) or control IgG2a and then with newborn rabbit complement (EFS B/FC, Besançon, France) for 1 h under agitation at room temperature. After washing, lysis was repeated for 30 min. CD25 depletion was confirmed by cytometry (< 0.7 % CD4⁺CD25⁺ T cells after CDC). CD25-depleted or control responder cells were stimulated in MLR assays in 96-well round-bottom plates (Sarstedt, Orsay, France) in triplicates for 5 days in complete medium at 37°C in a 5% CO₂ incubator. After a 5-d stimulation, cells were pulsed with 1µCi of [methyl-³H]-thymidine (NEN life Science Products, Boston, MA). After approximately 16 h of additional culture, cells were harvested and radioactivity was counted in a beta scintillation counter (Wallac Betaplate counter, Perkin-Elmer, Norwalk, CT). In the second assay, FACS-sorted CD4⁺ CD25⁺ T cells were added to CD25-depleted responder cells from naive BALB/c mice stimulated by allogeneic cells, as described above. To determine the mechanism(s) by which FACS-sorted CD4⁺CD25⁺ T cells exert their suppressive activity, we added CD4⁺CD25⁺ T cells above a cell culture insert (0.3 µm, BD Biosciences). We also investigated the neutralizing effect of various Abs at a final concentration of 5 µg/ml: anti-pan TGF-β polyclonal Ab, its control Ab (Sigma), anti-IL-10R (1B1.2, kindly provided by K. Moore, DNAX Research Institute, Palo Alto, CA, via H. Groux, Nice, France), its control mAb (Rat IgG1 mAb, GL113).

Quantitative Real-Time PCR (QRT-PCR) for Foxp3 mRNA

Total RNA was extracted using RNA extraction kit (Qiagen, Valencia, CA) according to the manufacturer's instructions and reverse transcribed using random hexamers and M-MLV reverse transcriptase (Life Technologies, Rockville, MD) to use as a template for QRT-PCR. QRT-PCR reactions were then performed in duplicates using gene specific probes and universal master mix (Qiagen) on an iCycler iQ thermocycler (Bio-Rad Laboratories, Marnes-la-Coquette, France). Primers and dual labeled fluorescent probes were designed using Primer Express® software (Applied Biosystems, Forster City, CA) to be specific for RNA but not for genomic DNA. Primer pairs and related probes were as follow (sense, anti-sense and probe respectively): Foxp3: 5'-CCCACCTACAGGCCCTTCTC-3', 5'-GGCATGGGCATCCACAGT-3' and 5'-FAM-GGACAGACCACACTTCATGCATCAGCTC-TAMRA-3'; GAPDH (used as endogenous reference): 5'-TTCACCACCATGGAGAAGGC-3', 5'-GGCATGGACTGTGGTCATGA-3' and 5'-FAM-TGCATCCTGCACCACCAACTGCTTAG-TAMRA-3'. For each sequence, a standard curve was generated with a dilution series of a known copy number of the target. The relative amount of each unknown sample was determined automatically with the iCycler iQ® software, using the threshold cycle (Ct). Data were expressed as normalized Foxp3 mRNA expression, which was obtained by dividing the relative amount of Foxp3 mRNA for each sample by the relative amount of GAPDH mRNA of the same sample.

Statistical analysis

Group comparisons of continuous data were made by Student's t or Mann-Whitney Rank Sum test. Survival data were analyzed using Kaplan-Maier survival analysis. *P*-values < 0.05 were considered as significant.

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References

1. Kamradt T and Mitchison NA (2001) Tolerance and autoimmunity. *N Engl J Med* 344: 655-64
2. Sakaguchi S (2000) Regulatory T cells: key controllers of immunologic self-tolerance. *Cell* 101: 455-8
3. Shevach EM (2002) CD4⁺ CD25⁺ suppressor T cells: more questions than answers. *Nat. Rev. Immunol.* 2: 389-400
4. Wood KJ and Sakaguchi S (2003) Regulatory T cells in transplantation tolerance. *Nat. Rev. Immunol.* 3: 199-210
5. Cohen JL, Trenado A, Vasey D, Klatzmann D and Salomon BL (2002) CD4⁺CD25⁺ immunoregulatory T Cells: new therapeutics for graft-versus-host disease. *J. Exp. Med.* 196: 401-6
6. Hoffmann P, Ermann J, Edinger M, Fathman CG and Strober S (2002) Donor-type CD4⁺CD25⁺ regulatory T cells suppress lethal acute graft-versus-host disease after allogeneic bone marrow transplantation. *J. Exp. Med.* 196: 389-99
7. Piccirillo CA, Letterio JJ, Thornton AM, McHugh RS, Mamura M, Mizuhara H and Shevach EM (2002) CD4⁺CD25⁺ regulatory T cells can mediate suppressor function in the absence of transforming growth factor beta1 production and responsiveness. *J. Exp. Med.* 196: 237-46
8. Groux H, O'Garra A, Bigler M, Rouleau M, Antonenko S, de Vries JE and Roncarolo MG (1997) A CD4⁺ T-cell subset inhibits antigen-specific T-cell responses and prevents colitis. *Nature* 389: 737-42
9. Weiner HL (2001). Induction and mechanism of action of transforming growth factor-beta-secreting Th3 regulatory cells. *Immunol. Rev.* 182: 207-14

10. Fontenot JD, Gavin MA and Rudensky AY (2003) Foxp3 programs the development and function of CD4+CD25+ regulatory T cells. *Nat. Immunol.* 4: 330-6
11. Hori S, Nomura T and Sakaguchi S (2003) Control of regulatory T cell development by the transcription factor Foxp3. *Science* 299: 1057-61
12. Khattri R, Cox T, Yasayko SA and Ramsdell F (2003) An essential role for Scurfin in CD4+CD25+ T regulatory cells. *Nat. Immunol.* 4: 337-42
13. Chen W, Jin W, Hardegen N, Lei KJ, Li L, Marinos N, McGrady G and Wahl SM (2003) Conversion of peripheral CD4+CD25- naive T cells to CD4+CD25+ regulatory T cells by TGF-beta induction of transcription factor Foxp3. *J. Exp. Med.* 198: 1875-86
14. Fantini MC, Becker C, Monteleone G, Pallone F, Galle PR and Neurath MF (2004) Cutting edge: TGF-beta induces a regulatory phenotype in CD4+CD25- T cells through Foxp3 induction and down-regulation of Smad7. *J. Immunol.* 172: 5149-53
15. Fu S, Zhang N, Yopp AC, Chen D, Mao M, Chen D, Zhang H, Ding Y and Bromberg JS (2004) TGF-beta induces Foxp3 + T-regulatory cells from CD4 + CD25 - precursors. *Am. J. Transplant.* 4: 1614-27
16. Sun EW and Shi YF (2001) Apoptosis: the quiet death silences the immune system. *Pharmacol. Ther.* 92: 135-45
17. Steinman RM, Turley S, Mellman I and Inaba K (2000) The induction of tolerance by dendritic cells that have captured apoptotic cells. *J. Exp. Med.* 191: 411-6
18. Albert ML (2004) Death-defying immunity: do apoptotic cells influence antigen processing and presentation?. *Nat. Rev. Immunol.* 4: 223-31
19. Fadok VA, Bratton DL, Konowal A, Freed PW, Westcott JY and Henson PM (1998) Macrophages that have ingested apoptotic cells in vitro inhibit proinflammatory cytokine production through autocrine/paracrine mechanisms involving TGF-beta, PGE2, and PAF. *J. Clin. Invest.* 101: 890-8

20. Huang FP, Platt N, Wykes M, Major JR, Powell TJ, Jenkins CD and MacPherson GG (2000) A discrete subpopulation of dendritic cells transports apoptotic intestinal epithelial cells to T cell areas of mesenteric lymph nodes. *J. Exp. Med.* 191: 435-44
21. Iyoda T, Shimoyama S, Liu K, Omatsu Y, Akiyama Y, Maeda Y, Takahara K, Steinman RM and Inaba K (2002) The CD8⁺ dendritic cell subset selectively endocytoses dying cells in culture and in vivo. *J. Exp. Med.* 195: 1289-302
22. Liu K, Iyoda T, Saternus M, Kimura Y, Inaba K and Steinman RM (2002) Immune tolerance after delivery of dying cells to dendritic cells in situ. *J Exp Med* 196: 1091-7
23. Morelli AE, Larregina AT, Shufesky WJ, Zahorchak AF, Logar AJ, Papworth G.D, Wang Z, Watkins SC, Falo LD Jr and Thomson AW (2003) Internalization of circulating apoptotic cells by splenic marginal zone dendritic cells: dependence on complement receptors and effect on cytokine production. *Blood* 101: 611-20
24. Gallucci S and Matzinger P (2001) Danger signals: SOS to the immune system. *Curr. Opin. Immunol.* 13: 114-9
25. Voll RE, Herrmann M, Roth EA, Stach C, Kalden JR and Girkontaite I (1997) Immunosuppressive effects of apoptotic cells. *Nature* 390: 350-1
26. Huynh ML, Fadok VA and Henson PM (2002) Phosphatidylserine-dependent ingestion of apoptotic cells promotes TGF-beta1 secretion and the resolution of inflammation. *J. Clin. Invest.* 109: 41-50
27. Byrne A and Reen DJ (2002) Lipopolysaccharide induces rapid production of IL-10 by monocytes in the presence of apoptotic neutrophils. *J. Immunol.* 168: 1968-77
28. Chen W, Frank ME, Jin W and Wahl SM (2001) TGF-beta released by apoptotic T cells contributes to an immunosuppressive milieu. *Immunity* 14: 715-25
29. Gao Y, Herndon JM, Zhang H, Griffith TS and Ferguson TA (1998) Antiinflammatory effects of CD95 ligand (FasL)-induced apoptosis. *J. Exp. Med.* 188: 887-96

30. Adler SH and Turka LA (2002) Immunotherapy as a means to induce transplantation tolerance. *Curr. Opin. Immunol.* 14: 660-5
31. Bittencourt MC, Perruche S, Contassot E, Fresnay S, Baron MH, Angonin R, Aubin F, Herve P, Tiberghien P and Saas P (2001) Intravenous injection of apoptotic leukocytes enhances bone marrow engraftment across major histocompatibility barriers. *Blood* 98: 224-30
32. Leenen PJ, Radosevic K, Voerman JS, Salomon B, van Rooijen N, Klatzmann D and van Ewijk W (1998) Heterogeneity of mouse spleen dendritic cells: in vivo phagocytic activity, expression of macrophage markers, and subpopulation turnover. *J. Immunol.* 160: 2166-73
33. Blazar BR, Lindberg FP, Ingulli E, Panoskaltsis-Mortari A, Oldenborg PA, Iizuka K, Yokoyama WM and Taylor PA (2001) CD47 (integrin-associated protein) engagement of dendritic cell and macrophage counterreceptors is required to prevent the clearance of donor lymphohematopoietic cells. *J. Exp. Med.* 194: 541-9
34. Jung S, Unutmaz D, Wong P, Sano G, De los Santos K, Sparwasser T, Wu S, Vuthoori S, Ko K, Zavala F, Pamer EG, Littman DR and Lang RA (2002) In vivo depletion of CD11c(+) dendritic cells abrogates priming of CD8(+) T cells by exogenous cell-associated antigens. *Immunity* 17: 211-20
35. Perruche S, Kleinclauss F, Bittencourt MC, Paris D, Tiberghien P and Saas P (2004) Intravenous infusion of apoptotic cells simultaneously with allogeneic hematopoietic grafts alters anti-donor humoral immune responses. *Am. J. Transplant.* 4: 1361-5
36. Fadok VA, Bratton DL, Rose DM, Pearson A, Ezekewitz RA and Henson PM (2000) A receptor for phosphatidylserine-specific clearance of apoptotic cells. *Nature* 405: 85-90
37. Perruche S, Kleinclauss F, Angonin R, Cahn JY, Deconinck E, Reininger L, Boucraut J, Tiberghien P and Saas P (2003) A single intravenous infusion of apoptotic cells, an

- alternative cell-based therapy approach facilitating hematopoietic cell engraftment, does not induce autoimmunity. *J. Hematother. Stem Cell Res.* 12: 451-9
38. Letterio JJ and Roberts AB (1998) Regulation of immune responses by TGF-beta. *Annu. Rev. Immunol.* 16: 137-61
 39. Bushell A, Karim M, Kingsley CI and Wood KJ (2003) Pretransplant blood transfusion without additional immunotherapy generates CD25+CD4+ regulatory T cells: a potential explanation for the blood-transfusion effect. *Transplantation* 76: 449-55
 40. Dzik WH (2003) Apoptosis, TGF beta and transfusion-related immunosuppression: Biologic versus clinical effects. *Transfus. Apheresis Sci.* 29: 127-9
 41. Snyder EL and Kuter DJ (2000) Apoptosis in transfusion medicine: of death and dying--is that all there is? *Transfusion* 40: 135-8
 42. Sun E, Gao Y, Chen J, Roberts AI, Wang X, Chen Z and Shi Y (2004) Allograft tolerance induced by donor apoptotic lymphocytes requires phagocytosis in the recipient. *Cell Death Differ.* 11: 1258-64
 43. Fadok VA, Bratton DL and Henson PM (2001) Phagocyte receptors for apoptotic cells: recognition, uptake, and consequences. *J. Clin. Invest.* 108: 957-62
 44. Kobie JJ, Wu RS, Kurt RA, Lou S, Adelman MK, Whitesell LJ, Ramanathapuram LV, Arteaga CL and Akporiaye ET (2003) Transforming growth factor beta inhibits the antigen-presenting functions and antitumor activity of dendritic cell vaccines. *Cancer Res.* 63: 1860-4
 45. Walker MR, Kasprovicz DJ, Gersuk VH, Benard A, Van Landeghen M, Buckner JH and Ziegler SF (2003) Induction of FoxP3 and acquisition of T regulatory activity by stimulated human CD4+CD25- T cells. *J. Clin. Invest.* 112: 1437-43
 46. Apostolou I and von Boehmer H (2004) In vivo instruction of suppressor commitment in naive T cells. *J. Exp. Med.* 199: 1401-8

47. Liang S, Alard P, Zhao Y, Parnell S, Clark SL and Kosiewicz MM (2005) Conversion of CD4⁺ CD25⁻ cells into CD4⁺ CD25⁺ regulatory T cells in vivo requires B7 costimulation, but not the thymus. *J. Exp. Med.* 201: 127-37
48. Colson YL, Christopher K, Glickman J, Taylor KN, Wright R and Perkins DL (2004) Absence of clinical GvHD and the in vivo induction of regulatory T cells following facilitating cell transplantation. *Blood* 104: 3829-35
49. Taylor PA, Panoskaltsis-Mortari A, Swedin JM, Lucas PJ, Gress RE, Levine BL, June CH, Serody JS and Blazar BR (2004) L Selectin^{hi} but not the L Selectin^{lo} CD4⁺25⁺ T regulatory cells are potent inhibitors of GVHD and BM graft rejection. *Blood* 104: 3804-12
50. Hanash AM and Levy RB (2005) Donor CD4⁺CD25⁺ T cells promote engraftment and tolerance following MHC-mismatched hematopoietic cell transplantation. *Blood* 105: 1828-36
51. Contassot E, Ferrand C, Angonin R, Cohen JL, de Carvalho Bittencourt M, Lorchel F, Laithier V, Cahn JY, Klatzmann D, Herve P and Tiberghien P (2000) Ganciclovir-sensitive acute graft-versus-host disease in mice receiving herpes simplex virus-thymidine kinase-expressing donor T cells in a bone marrow transplantation setting. *Transplantation* 69: 503-8
52. Dumitriu IE, Mohr W, Kolowos W, Kern P, Kalden JR and Herrmann M (2001) 5,6-carboxyfluorescein diacetate succinimidyl ester-labeled apoptotic and necrotic as well as detergent-treated cells can be traced in composite cell samples. *Anal. Biochem.* 299: 247-52
53. Perruche S, Kleinclauss F, Lienard A, Robinet E, Tiberghien P and Saas P (2004) A single-platform approach using flow cytometry and microbeads to evaluate immune reconstitution in mice after bone marrow transplantation. *J. Immunol. Methods* 294: 53-66

FIGURE LEGENDS

Figure 1 Recipient macrophages are mainly involved in the graft-facilitating effect of apoptotic spleen cell infusion. **(a)** Green-PKH- or CFSE-labeled apoptotic cells (detectable in the FL1 channel) were used to explore phagocytes involved in the apoptotic cell uptake. Left panel: 45 min after BMT, fluorescent apoptotic cells infused simultaneously with BM graft were found in splenic DC (F4/80^{low}CD11c⁺FL1⁺; white arrows) as well as in macrophages (F4/80^{high}CD11c⁺FL1⁺; black arrows). Results from a representative experiment out of 4. Middle panel: non-fluorescent apoptotic cells used as controls. Right panel: kinetics of the appearance of CFSE⁺CD11c⁺ DC (■) and CFSE⁺F4/80⁺ macrophages (●) after infusion of CFSE-labeled apoptotic cells. The percentage of CFSE⁺ cells contained within the indicated splenic cell population is listed on the y axis. *n* = 3 mice per time point. Bars represent S.D.

(b) Sca-1 cell sorting was used to deplete phagocytes from the BM (left panel: a representative sorting experiment out of 4). Right panel: donor engraftment after infusion of total C57BL/6 BM (10⁶ cells) or sca-1-enriched graft (Sca-1, 10⁵ cells) with (Apo cells, hatched bars) or without (white bars) apoptotic cells. Pooled results from 3 independent experiments (at least 20 mice/group) expressed in % of engrafted mice. * *P* < 0.05. **(c)** Clodronate-loaded liposomes were infused before BMT to deplete host splenic phagocytosing cells. Left panel: flow cytometric CD11b staining shows the effective depletion of CD11b⁺ macrophages at day 3 after clodronate-liposome infusion. CD11b staining in PBS loaded-liposome treated mice was shown as control. Right panel: donor engraftment after infusion of total BM (10⁶ cells) with (hatched bars) or without (white bars) apoptotic cells in mice treated by PBS-liposomes or clodronate-liposomes. **(d)** Recipient CD11c⁺ DC were depleted at day-1 before BMT using a single infusion of diphtheria toxin (DT). Top panel: a representative depletion of eGFP⁺CD11c⁺ cells after a 20 h DT treatment. Bottom panel: donor engraftment after infusion of total BM (10⁶ cells) with (hatched bars) or without (open bars) apoptotic cells

in DT-treated transgenic mice. Pooled results from 2 independent experiments expressed in % of engrafted mice. * $P < 0.05$.

Figure 2 Apoptotic spleen cell infusion simultaneously with a bone marrow graft induces an *in vivo* TGF- β -dependent splenic expansion of CD4⁺CD25⁺ T cells. **(a)** Splenic CD4⁺CD25⁺ T cells increase after apoptotic spleen cell infusion. These cells were evaluated by cytometry in different groups: naive mice, engrafted and non-engrafted mice given apoptotic cells, engrafted mice given only a higher number of BM cells (3×10^6) and engrafted mice given a higher conditioning regimen (7 Gy). Boxes represent mean $\pm$ SEM, bars the S.D. and circles the highest and lowest values. *: $P < 0.01$. **(b)** TGF- β neutralization inhibits apoptotic spleen cell-induced splenic CD4⁺CD25⁺ T cell increase. The percentage of splenic CD4⁺CD25⁺ T cells was evaluated 7-9 weeks post-graft in TGF- β mAb-treated mice ($n = 7$) vs in irrelevant isotype Ab-treated mice ($n = 9$). Pooled results of 2 independent experiments. *: $P < 0.01$.

Figure 3 Apoptotic spleen cell infusion simultaneously with a bone marrow graft induces *in vivo* splenic expansion of CD4⁺CD25⁺ regulatory T cells expressing high levels of Foxp3 mRNA and exhibiting *in vitro* cell-to-cell contact-dependent suppression. **(a)** Expanded splenic CD4⁺CD25⁺ T cells from engrafted and non-engrafted mice were characterized 7-9 weeks post-BMT. CD25, H-2^d and CD62L expressions were evaluated on the CD4⁺CD3⁺ T cell gate (CD3⁺ ; CD4⁺ ; SSC vs FSC), whereas intracellular CTLA-4 expression was evaluated on the CD3⁺CD4⁺CD25⁺ T cell gate. **(b)** Seven to nine weeks post-BMT, cell-sorted splenic CD4⁺CD25⁺ T cells were analyzed for Foxp3 mRNA expression in engrafted ($n = 2$, hatched bars) and non-engrafted ($n = 1$, open bar) mice that had been given apoptotic cells plus BM cells. Relative Foxp3 mRNA expression was obtained by dividing relative Foxp3 expression in the CD4⁺CD25⁺ T cell fraction by that of the CD4⁺CD25⁻ T cell fraction.

(c) Foxp3 mRNA expression is assessed in whole spleen of either mice given BM alone (left open bars, $n = 4$), mice given apoptotic cells plus BM (hatched bars, $n = 6$) 7-9 week post-BMT. Foxp3 mRNA expression in the spleen of naive BALB/c mice (right open bars, $n = 8$) was shown as control. Results are expressed as mean $\pm$ SEM of normalized Foxp3 expression (obtained by dividing the relative amount of Foxp3 mRNA for each sample by the relative amount of GAPDH mRNA of the same sample). (d) Splenic CD4⁺ T cells from engrafted (left panel, $n = 3$) or non-engrafted (right panel, $n = 2$) BALB/c mice given donor FVB BM and apoptotic cells were cultured with or without allogeneic (FVB donor or C57BL/6 third party) stimulator cells. T cells were CD25-depleted (open bars) or not (hatched bars). MLR proliferation was assessed by [³H]thymidine uptake (cpm). *: $P < 0.01$. (e) Cell-sorted CD4⁺CD25⁺ T cells were added to a MLR between stimulator irradiated splenic FVB donor cells and CD25-depleted responder BALB/c recipient CD4⁺ T cells ($n = 2$) with or without (Ø) anti-IL10R, anti-TGF- β mAb or both. A transwell was also used to separate the MLR from sorted CD4⁺CD25⁺ T cells. Results are expressed as relative proliferation obtained by dividing the CD4⁺ T cell proliferation in response to allogeneic stimulators by the proliferation obtained in similar conditions but in the presence of blocking Abs or transwell. [³H]thymidine uptake > 9000 cpm. *: $P < 0.05$.

Figure 4 Depletion of CD11c⁺ dendritic cells has no effect on CD62L^{high}CD4⁺CD25⁺ T cell increase induced by apoptotic spleen cell infusion. Recipient CD11c⁺ DC were depleted at day -1 before BMT using a single infusion of diphtheria toxin (DT). CD11c/eGFP/DTR transgenic mice given donor apoptotic cells plus BM were treated (left box, $n = 8$) or not (right box, $n = 5$) with DT. CD62L⁺CD4⁺CD25⁺ T cells were analyzed by cytometry 7-9 weeks post-BMT. Boxes represent mean $\pm$ SEM, bars the SD.

Figure 5 Apoptotic spleen cell infusion simultaneously with a bone marrow graft induces an early increase of CD62L⁺CD4⁺CD25⁺ T cells of both host and donor origin. **(a)** Host macrophages are involved in the early increase of CD62L⁺CD4⁺CD25⁺ T cells induced by apoptotic spleen cell infusion. Splenic CD62L⁺CD4⁺CD25⁺ T cells were analyzed by cytometry at different time points after the infusion of FVB BM alone (□, *n*=5), or FVB BM plus FVB apoptotic cells (■, *n*=5). Such cells were also analyzed in BALB/c mice pre-treated with clodronate-liposomes and grafted with FVB BM plus FVB apoptotic cells (▲, *n*=3) and in irradiated BALB/c mice (Δ, *n* = 3). *: *P* < 0.05. **(b)** Percentage of donor CD62L⁺CD4⁺CD25⁺ T cells in the spleen of mice given FVB BM alone (□, *n*=5) or BM plus apoptotic spleen cells (■, *n*=5) at different early time points after BMT. *: *P* < 0.05.

Figure 6 CD25⁺ cell depletion significantly reduces the number of circulating donor-derived cells after apoptotic spleen cell infusion. Percentage of donor-derived cells was evaluated 7-9 week post-graft in the spleen of mice given only BM (●, *n*=10), BM and apoptotic cells plus anti-CD25 mAb (▲, *n*=10) or plus irrelevant mAb (■, *n*=12). Number of engrafted mice in each group was shown. Dotted line indicates 15% of donor-derived cells corresponding to engraftment. Pooled results of 2 independent experiments. *: *P* < 0.05.

Figure 7 CD25⁺ cell depletion prevents the protecting effect of donor apoptotic spleen cell administration on graft-versus-host disease occurrence. **(a)** Cumulative survival was assessed in the GvHD model in mice receiving BM plus splenic T cells and donor apoptotic spleen cells (▲) or not (control GvHD group; □). Mice receiving BM alone (●) or only lethally irradiated (○) were also used as control. Results of a representative experiment out of 4 are expressed in % of cumulative survival. **(b)** Donor apoptotic spleen cells delays lethal GvHD occurrence in a dose-dependent manner. Median survival time was assessed in mice receiving

increasing number of apoptotic cells (2×10^6 , 2×10^7 or 10^8 apoptotic spleen cells; hatched bars) or not (GvHD Ctrl group; open bar) in addition to BM and splenic T cells. Pooled results from 4 independent experiments (10 mice per group, excepted for ctrl group $n=5$) are expressed in median survival time (day) $\pm$ SD. (c) Delayed CD25⁺ cell depletion abolishes the protective effects of donor apoptotic spleen cell infusion on lethal GvHD occurrence. Cumulative survival was assessed in mice receiving BM plus splenic T cells (GvHD Ctrl group, $\square$); with apoptotic cells and treated at day 3 and 6 by anti-CD25 mAb ($\bullet$) or irrelevant IgG1 control ($\blacksquare$). Results of a representative experiment out of 3 are expressed in % of cumulative survival. 10 mice per group.

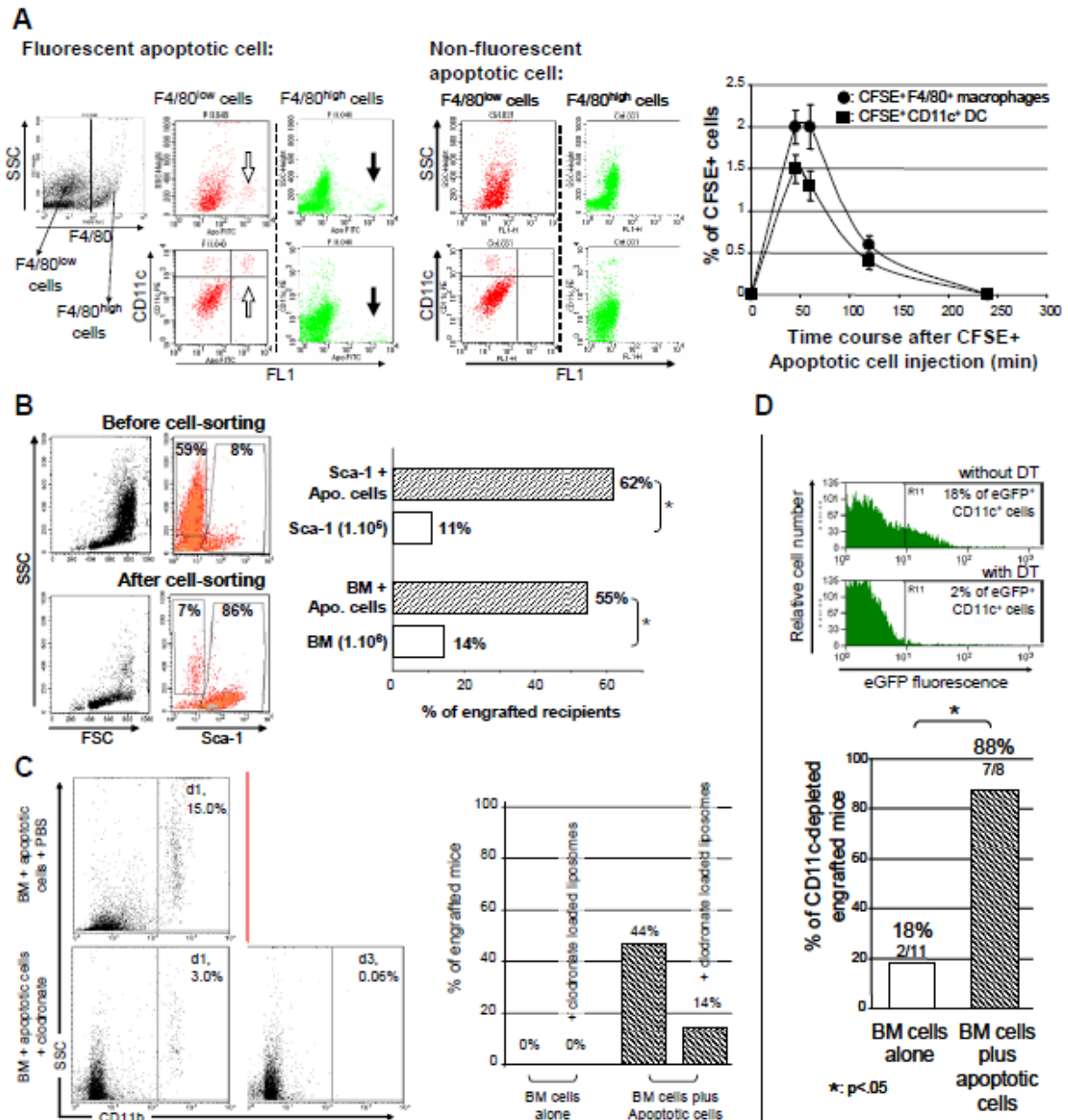


Figure 1.

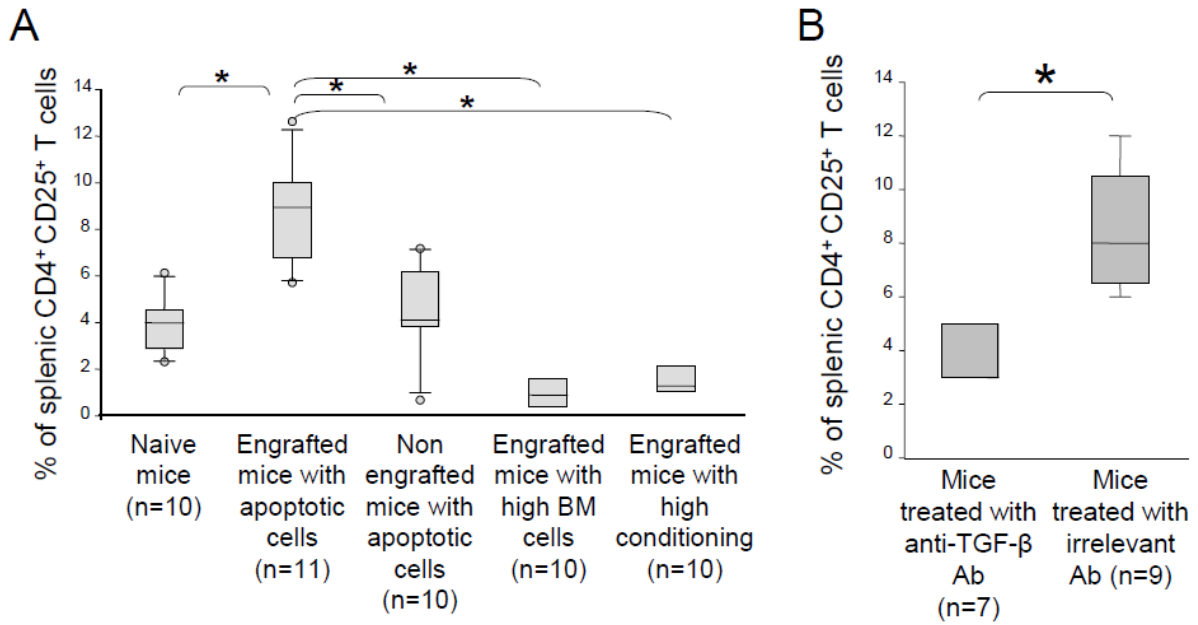


Figure 2.

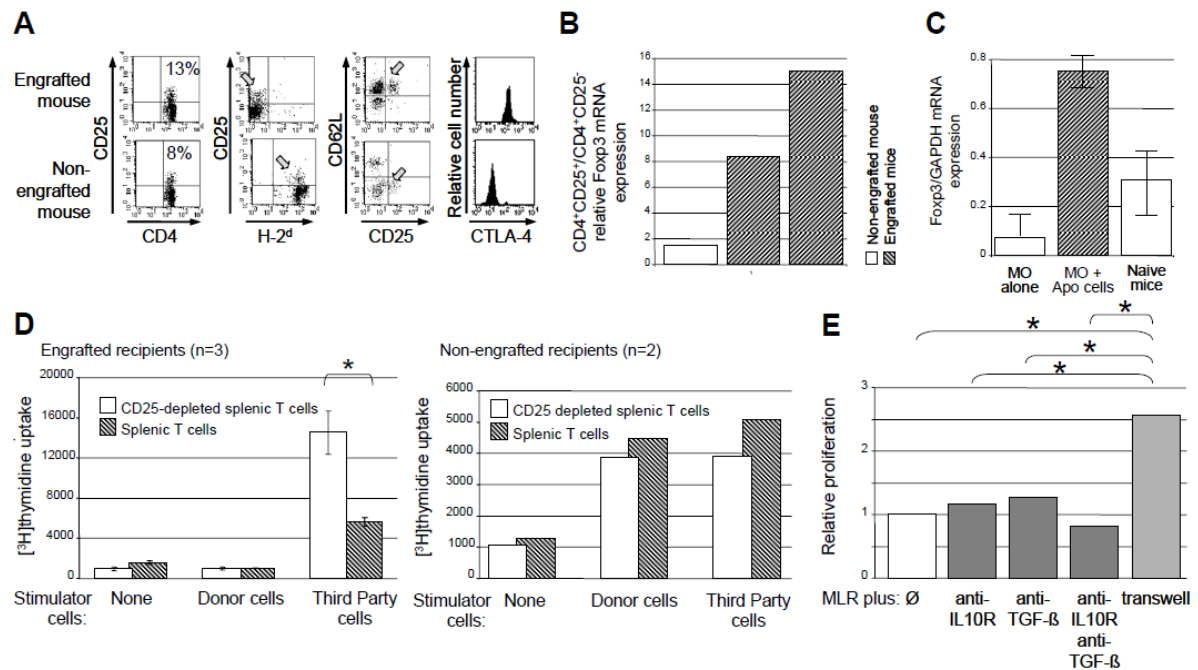


Figure 3

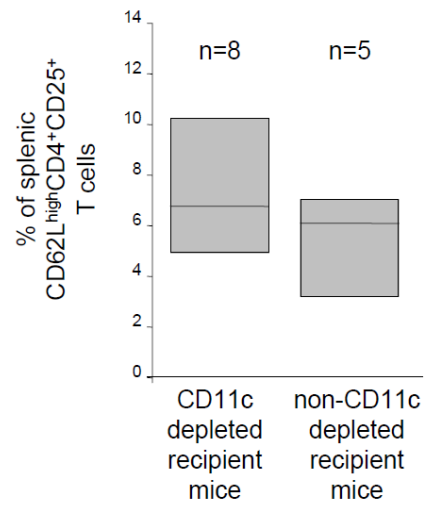


Figure 4.

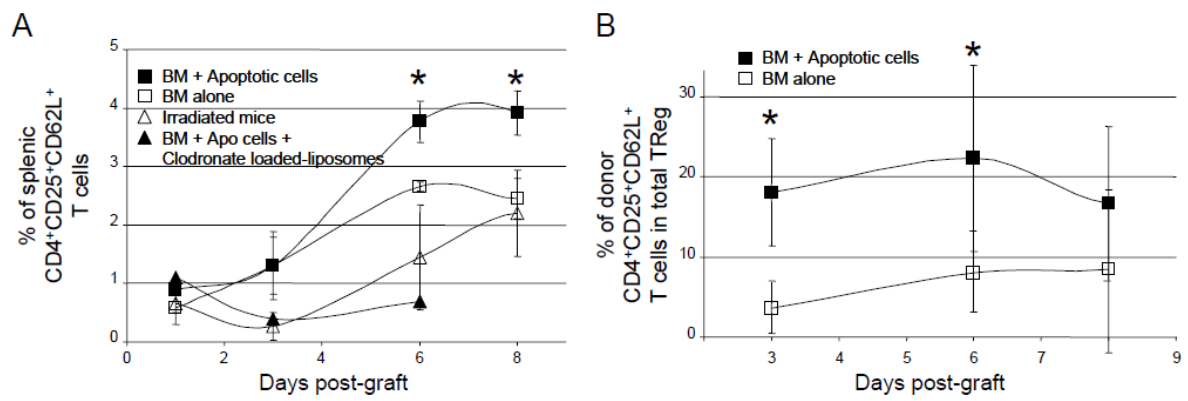


Figure 5

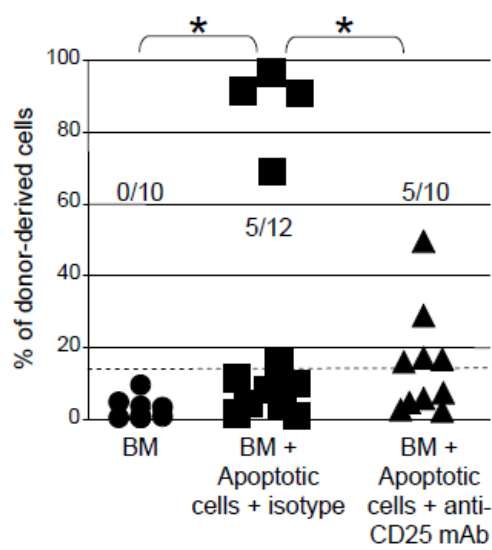


Figure 6.

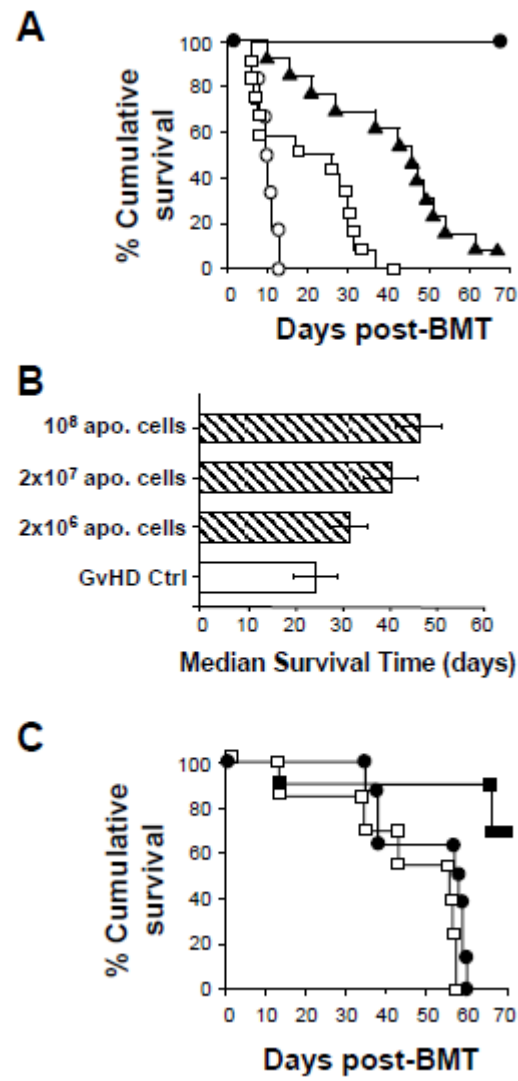
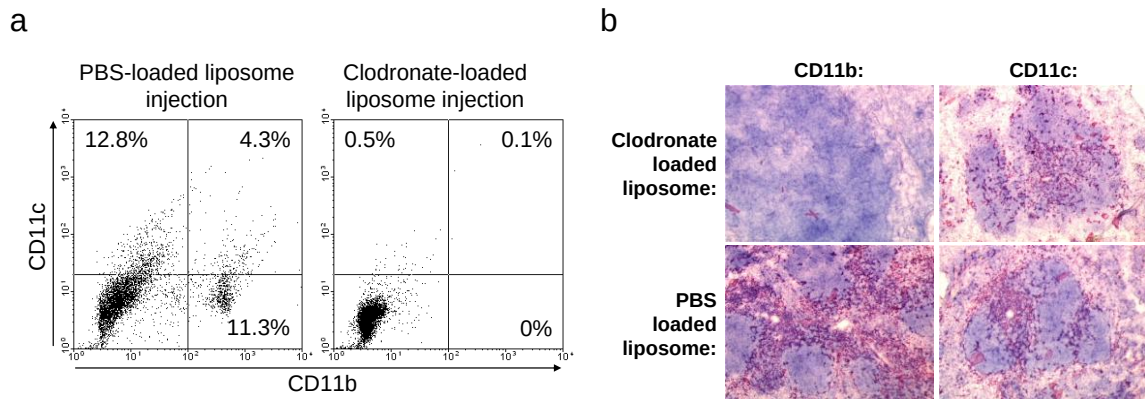


Figure 7.



Supplement Figure 1:

Clodronate-loaded liposomes infused before BMT deplete host splenic phagocytes. **(a)** A representative staining of splenic phagocytes using anti-CD11c and CD11b antibodies, 24 hours after the infusion of PBS-loaded liposomes or clodronate-loaded liposomes. **(b)** Left panels: immuno-histological CD11b staining shows the effective depletion of CD11b⁺ macrophages in the recipient spleen 12 h after clodronate-liposome infusion (top panel). A CD11b staining was observed when PBS-liposomes were infused (bottom panel) (magnified: 10X). Right panels: immuno-histological CD11c staining reveals that not all splenic DC subsets were depleted by clodronate-loaded liposome infusion, due to their anatomic location, as previously reported (Leenen, P. J., K. Radosevic, J. S. Voerman, B. Salomon, N. van Rooijen, D. Klatzmann, and W. van Ewijk. 1998. Heterogeneity of mouse spleen dendritic cells: in vivo phagocytic activity, expression of macrophage markers, and subpopulation turnover. *J Immunol* 160:2166).