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Apoptotic cells suppress mast cell inflammatory responses via the CD300a immunoreceptor

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When a cell undergoes apoptosis, phosphatidylserine (PS) is exposed on the outer leaflet of the plasma membrane. PS acts as an "eat-me" signal to direct phagocytes expressing PS receptors to engulf the apoptotic cell. We recently reported that the immunoreceptor CD300a, which is expressed on myeloid cells, is a PS receptor. We show that CD300a does not facilitate macrophage phagocytosis of apoptotic cells. Instead, CD300a delivers an inhibitory signal in mast cells to suppress production of LPS-induced inflammatory cytokines and chemokines. After cecal ligation and puncture (CLP), when a large number of cells undergo apoptosis in the peritoneal cavity, CD300a-deficient peritoneal mast cells produced more chemoattractant and recruited more neutrophils than did wild-type (WT) mast cells. As a result, CD300a-deficient mice showed increased neutrophil recruitment and improved bacterial clearance in the peritoneal cavity, and survived longer than WT mice. Antibody blockade of CD300a–PS interactions improved bacterial clearance and extended survival of WT mice subjected to CLP. These results indicated that CD300a is a nonphagocytic PS receptor that regulates mast cell inflammatory responses to microbial infections.

Abbreviations used: BMMC, BM-derived mast cell; CAD, caspase-activated DNase; CLP, cecal ligation and puncture; ITIM, immunoreceptor tyrosine-based inhibition motif; MFG-E8, milk fat globule EGF factor 8; PS, phosphatidylserine; TIM-4, T cell immunoglobulin– and mucin domain–containing molecule 4.

Apoptosis, referred to as programmed cell death, is one of the most important events in the cell fate. Several cells undergo apoptosis every day in physiological and pathological settings in the body. When a cell undergoes apoptosis, phosphatidylserine (PS) is exposed on the outer leaflet of the plasma membrane and signals phagocytes to engulf the apoptotic cells (Ravichandran and Lorenz, 2007). Several receptors for PS are expressed on phagocytes and are involved in clearing apoptotic cells (Ravichandran and Lorenz, 2007; Zhou, 2007; Nagata et al., 2010). For example, T cell immunoglobulin– and mucin domain–containing molecule 4 (TIM-4), TIM-1, and TIM-3 are expressed on macrophages and/or dendritic cells and mediate engulfment of apoptotic cells upon binding PS (Kobayashi et al., 2007; Miyashita et al., 2007). BA11 (brain-specific angiogenesis inhibitor 1; Park et al., 2007) and stabilin-2 (Park et al., 2008), which are expressed on neuron (Mori et al., 2002) and the sinusoidal endothelial cells of the spleen, lymph nodes, and BM (Harris et al., 2007), respectively, were also reported to be PS receptors for apoptotic cells.Engulfment of apoptotic cells also involves the bridging molecules that recognize PS. Milk fat globule EGF factor 8 (MFG-E8), which is expressed by tingible body macrophages and follicular dendritic cells at the germinal centers in the spleen and lymph nodes—intermediates between apoptotic cells and phagocytes—by binding both PS and αβ3 or αβ5 integrin on the phagocytes, stimulating the engulfment of apoptotic cells (Hanayama et al., 2002). Similarly,

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Gas6 (growth arrest–specific 6) and protein S, which are abundant in the plasma and bind PS and TAM family members (Tyr3, Axl, and Mer), are also bridging molecules between apoptotic cells and phagocytes (Nakano et al., 1997; Scott et al., 2001). However, whether PS receptors deliver signals that lead to cellular responses other than phagocytosis is unclear.

Activation of immune cells is regulated by positive and negative signals triggered by activating and inhibitory cell surface immunoreceptors, respectively. These immunoreceptors play important roles in regulation of immune responses (Ravetch and Lanier, 2000; Lanier, 2001). Inhibitory receptors are characterized by the immunoreceptor tyrosine-based inhibition motif (ITIM) in their cytoplasmic domains. The prototype 6-aa sequence for ITIM is (I/V/L/S)-x-Y-x-x-(L/V) (x denotes any amino acid), whose tyrosine is phosphorylated upon ligand binding, providing a docking site for the recruitment of SH2 (Src homology 2)–containing cytoplasmic phosphatases (Malbec et al., 1998; Smith et al., 1998) and shutting down activation signals by dephosphorylation of intracellular substrates at the earliest steps of the activation response. The ITIM-bearing cell surface immunoreceptors, including certain NK receptors, Fc receptors (FcRIIb), and others, play a central role in mediating negative signals in both lymphoid and myeloid cells (Daëron et al., 2008).

CD300 is a multigene family consisting of seven genes on human chromosome 17 (Clark et al., 2000, 2001). CD300 molecules are members of Ig superfamily bearing one Ig-like domain in the extracellular portion. The mouse counterparts of CD300 molecules, which were reported to be myeloid-associated Ig-like receptor (MAIR; Yotsumoto et al., 2003; Okoshi et al., 2005; Nakahashi et al., 2007; Can et al., 2008; Nakano et al., 2008; Nakano-Yokomizo et al., 2011)/CMRF-35–like molecule (CLM; Chung et al., 2003; Fujimoto et al., 2006; Xi et al., 2010)/leukocyte mono-Ig-like receptor (LMIR; Kumagai et al., 2003; Izawa et al., 2007; Enomoto et al., 2010)/DigR (Luo et al., 2001; Shi et al., 2006), were encoded by nine genes on a small segment of mouse chromosome 11, the syntenic region of human chromosome 17 (Chung et al., 2003; Nakano et al., 2007). CD300 molecules are preferentially expressed on myeloid cells, including macrophages, neutrophils, DCs, and/or mast cells, and may regulate activation of these cells. One of the CD300 molecules, CD300a (also called MAIR-I [Yotsumoto et al., 2003], LMIR1 [Kumagai et al., 2003], or CLM-8 [Chung et al., 2003] in mice, and IRp60 [Cantoni et al., 1999] or CMRF-35H [Clark et al., 2000] in human), has a long cytoplasmic region containing the consensus ITIM sequence. Upon cross-linking with monoclonal antibodies, CD300a inhibits FcεRI-mediated

streptavidin. These cells were then analyzed by flow cytometry. The open histograms show CD300a expression on the gates of CD11b+F4/80+ and c-Kit+ FcεRI+ cells. The closed histograms show isotype control. Experiments were performed three times with similar results. The results of one experiment are shown (B–E).
signals, resulting in the suppression of degranulation from human and mouse mast cells in vitro (Yotsumoto et al., 2003; Okoshi et al., 2005; Munitz et al., 2006; Karra et al., 2009). In addition, CD300a modulates inflammatory responses by myeloid cells (Alvarez et al., 2008; Ju et al., 2008). CD300a is also expressed on human—but not mouse—NK cells and involved in cytotoxic function (Cantoni et al., 1999; Lankry et al., 2010). We have recently identified CD300a as a new PS receptor (Nakahashi-Oda et al., 2012). However, the physiological role of CD300a remained undetermined.

To explore the physiological role of CD300a, we generated mice deficient in Cd300a. We describe that CD300a does not stimulate engulfment of apoptotic cells by phagocytes but, rather, inhibits inflammatory cytokine and chemokine production from mast cells upon binding to PS in vitro and in vivo.

RESULTS
CD300a does not mediate phagocytosis
Several receptors for PS are expressed on phagocytes and are involved in clearing apoptotic cells in physiological and pathological settings (Scott et al., 2001; Hanayama et al., 2002; Kobayashi et al., 2007; Miyashita et al., 2007; Park et al., 2007, 2008). Because PS mediates an “eat-me” signal to phagocytes such as macrophages (Fadok et al., 1992; Savill et al., 2002), we generated CD300a-deficient (Cd300a−/−) mice (Fig. 1). Cd300a−/− mice lacked the expression of Cd300a mRNA and Cd300a protein but showed normal expression of neighboring genes to Cd300a in the Cd300 family gene cluster on chromosome 11 (Fig. 1), indicating that Cd300a−/− mice were correctly generated. We examined whether Cd300a is involved in phagocytosis of apoptotic cells by using macrophages from Cd300a−/− mice and apoptotic thymocytes from caspase-activated DNase (CAD)−/− mice. CAD−/− cells do not undergo apoptotic DNA fragmentation, but their DNA is degraded in phagocytes after they are engulfed (Nagata, 2005). WT or Cd300a−/− peritoneal resident macrophages were cocultured with dexamethasone-induced apoptotic CAD−/− thymocytes for 2 h, stained with TUNEL, and analyzed by laser-scanning confocal microscopy. The frequencies of WT and Cd300a−/− peritoneal macrophages carrying a given number of apoptotic cells were comparable (Fig. 2 A). Peritoneal resident macrophages also express several receptors, including TIM-1, TIM-4, and αβ3 (Kobayashi et al., 2007; Miyashita et al., 2007; Fig. 3 A), that directly or indirectly bind PS and are involved in engulfment of apoptotic cells (Kuchroo et al., 2008). To examine whether these PS receptors had functional redundancy that masked the CD300a phagocytic function, we established NIH 3T3 transfectants stably expressing either Cd300a or TIM-4 (Fig. 2 B). We labeled apoptotic thymocytes with pHrodo succinimidyl ester, a pH-sensitive fluorescent dye, which can be detected when they are engulfed as a result of the increased postphagocytic light emission (Miksa et al., 2009). The NIH 3T3 transfectants or parental NIH 3T3 cells were cocultured with pHrodo dye–labeled apoptotic thymocytes and analyzed by flow cytometry (Fig. 2 C). NIH 3T3 or NIH 3T3 transfectants were also analyzed by flow cytometry (D). Data are representative of more than three independent experiments (A–D).
Figure 3. CD300a inhibits LPS-induced cytokine secretion from mast cells. (A) Expression of PS receptors. Peritoneal resident macrophages and BMMCs were stained with a biotin-conjugated monoclonal antibody to TIM-1 followed by PE-conjugated streptavidin, a PE-conjugated monoclonal antibody to TIM-4, and an Alexa Fluor 488–conjugated monoclonal antibody to mouse CD300a (open histograms), and analyzed by flow cytometry. The closed histograms show isotype control. These cells were also subjected to RT-PCR to analyze expression of mRNA indicated. (B–D) WT or Cd300a−/− BMMCs mixed with apoptotic cells at a ratio of 1:0.1 were stimulated with 1 µg/ml LPS for 4 h. The culture supernatant was subjected to proteome analyses (B) or ELISA (C; n = 6) in the absence (B and C) or presence (C) of D89E MFG-E8. After culture, intracellular cytokine staining was also performed in BMMCs (D; n = 6). (E–G) RBL-2H3 transfectants expressing Flag-tagged WT or mutated CD300a, in which the tyrosines Y233, Y258, Y270, and/or Y299 were replaced with phenylalanine or the cytoplasmic region was deleted (Del; E), were cocultured with apoptotic cells at a ratio of 1:0.1 in the presence of 100 ng/ml LPS for 4 h (F) or the indicated times (G). Cells were immunoprecipitated with anti-Flag and immunoblotted with anti-SHP-1 (F), anti-phosphotyrosine...
analyses also demonstrated that a pHrodo signal was detected only in TIM-4, but not CD300a, transfected (Fig. 2 D). Together, these results indicated that CD300a does not mediate phagocytosis of apoptotic cells by macrophages.

**PS delivers an inhibitory signal in mast cells via CD300a**

CD300a is also expressed on mast cells. To address whether apoptotic cells affect mast cell activation via CD300a, we generated BM-derived mast cells (BMMCs) from *Cd300a*−/− or WT mice. Unlike macrophages, mast cells do not express the PS receptors TIM-1, TIM-4, and stablin-2, although they do express CD300a and αv integrin (Fig. 3 A). We examined whether PS binding to CD300a has any effect on LPS-induced cytokine or chemokine production from BMMCs by protease analyses. WT or *Cd300a*−/− BMMCs were cocultured with apoptotic cells at a ratio of 1:0.1 in the presence of LPS for 4 h. *Cd300a*−/− BMMCs produced greater amounts of several chemokines and cytokines, including MCP-1 and IL-13, compared with WT BMMCs (Fig. 3 B). We therefore performed quantitative analysis of MCP-1 and IL-13 in addition to a proinflammatory cytokine TNF by ELISA. Although we did not detect any cytokines or chemokines in the culture supernatants in the absence of stimuli, stimulation with 1 µg/ml LPS induced both WT and *Cd300a*−/− BMMCs to produce TNF, IL-13, and MCP-1; however, *Cd300a*−/− BMMCs produced them at significantly higher concentrations (Fig. 3 C). Flow cytometry analyses also detected significantly more of these cytokines and chemokines in the cytoplasm of *Cd300a*−/− BMMCs than in the cytoplasm of WT BMMCs 4 h after stimulation with LPS (Fig. 3 D). However, in the presence of a variant of MFG-E8 containing a point mutation (D89E) in the RGD motif (D89E MFG-E8), which is able to bind PS but is not able to bind αvβ3 integrin (Hanyama et al., 2002), the levels of these cytokines and chemokines were comparable in WT and *Cd300a*−/− BMMCs (Fig. 3 C), suggesting that CD300a–PS interaction inhibits these cytokines’ and chemokines’ production from BMMCs.

*Cd300a* contains the five tyrosines at residues 233, 258, 270, 299, and 313 in the cytoplasmic domain, and Y258 and Y270 consist of the consensus ITIM sequence ([I/V/L/S]xYxx[L/V]). We previously reported that Y258 and Y270 are responsible for phosphorylation of *Cd300a* and recruitment of SHP-1 in a rat basophilic leukemia cell line (RBL-2H3) upon stimulation with pervanadate (Okoshi et al., 2005). We found that Y258 and/or Y270 were phosphorylated and involved in SHP-1 recruitment in RBL-2H3 transfectants expressing WT or mutated *Cd300a* when these cells were cocultured with apoptotic cells in the presence of LPS (Fig. 3, E–G). We have recently reported that *Cd300a* also recruited SHP-1 in BMMCs when BMMCs were cocultured with apoptotic cells in the presence of LPS (Nakahashi-Oda et al., 2012). To examine whether SHP-1 is involved in *Cd300a*-mediated signaling, we knocked down *Ptpn6* with a small interfering RNA (siRNA) to create SHP-1–deficient (*Ptpn6-KD*) WT and *Cd300a*−/− BMMCs (Fig. 3 H). Whereas the control *Cd300a*−/− BMMCs produced significantly more TNF than did WT BMMCs after stimulation with LPS for 4 h, there was no significant difference in TNF production between *Ptpn6-KD* WT and *Ptpn6-KD* *Cd300a*−/− BMMCs (Fig. 3 I). Collectively, these results indicate that upon binding to PS, *Cd300a* recruits SHP-1 and mediates an inhibitory signal in BMMCs, resulting in the suppression of cytokines and chemokines secretion.

We next examined whether *Cd300a* also recruits SHP-1 and delivers an inhibitory signal in macrophages upon binding to PS. WT or *Cd300a*−/− peritoneal resident macrophages were cocultured with apoptotic thymocytes at 1:0.1 ratios in the presence of LPS, demonstrating that *Cd300a* also recruited SHP-1 in peritoneal resident macrophages (Fig. 3 J). Moreover, the production of TNF and IL-10 by *Cd300a*−/− peritoneal macrophages was significantly greater than that by WT peritoneal macrophages (Fig. 3 K), indicating that PS binding of *Cd300a* inhibits cytokine production by macrophages as well as mast cells.

**CD300a-deficient mice show longer survival after cecal ligation and puncture (CLP)**

TNF, IL-13, and MCP-1 produced by mast cells are chemotaxtants for neutrophils and play an important role in bacterial clearance in a CLP peritonitis model in mice (Echtenacher et al., 1996; Malaviya et al., 1996; Baumhofer et al., 1998; Matsukawa et al., 1999; Marshall, 2004). Therefore, we hypothesized that *Cd300a* affects immune regulation by mast cells at the site of peritonitis, where large numbers of cells undergo apoptosis in the peritoneal cavity (Hotchkiss and Nicholson, 2006). In fact, we observed that >10% of cells in the peritoneal cavity 4 h after CLP were apoptotic cells, as determined by staining with Annexin V (Fig. 4 A). To test the hypothesis, we subjected WT and *Cd300a*−/− mice to CLP and observed that *Cd300a*−/− mice survived significantly longer than did WT mice after CLP (Fig. 4 B).

To elucidate the mechanism responsible for the longer survival advantage of the *Cd300a*−/− mice in this model, we measured bacterial content in the peritoneal cavity 4 h after CLP. *Cd300a*−/− mice had significantly fewer bacterial colony-forming units (CFUs) than did WT mice (Fig. 4 C). Because we did not observe any differences in the number and type of commensal bacteria between the two mouse genotypes (G), or anti-Flag (F and G). (H and I) BMMCs were transfected with control siRNA (Ctrl) or SHP-1 siRNA and analyzed by immunoblotting with antibodies indicated (H). The mixture of these BMMCs and apoptotic cells were stimulated with 1 µg/ml LPS for 4 h and analyzed for TNF production by ELISA (I; n = 3). (J and K) *Cd300a*−/− or WT peritoneal resident macrophages were cocultured with apoptotic cells at a ratio of 1:0.1 in the presence of LPS for 4 h, immunoprecipitated with anti-*Cd300a*, and immunoblotted with anti-SHP-1 or anti-*Cd300a* (J). TNF and IL-10 in the culture supernatants were analyzed by ELISA (n = 3; K). Data are representative of three independent experiments. *P < 0.05; **P < 0.01, Student’s t test. Error bars show SD.
results indicated that neutrophils play an important role in the survival of mice after CLP.

CD300a on mast cells is critical for survival of mice after CLP

In the early phase of the CLP peritonitis model, mast cells play an important role in recruitment of neutrophils into the peritoneal cavity by secretion of chemoattractants for neutrophils, such as TNF, and prolong the survival (Echtenacher et al., 1996; Malaviya et al., 1996). We have demonstrated that Cd300a−/− BMMCs produced more chemoattractants for neutrophils—including TNF, IL-13, and MCP-1—in response to LPS than WT BMMCs in vitro (Fig. 3, C and D). To examine whether CD300a on mast cells is involved in neutrophil recruitment and longer survival, WT and Cd300a−/− mice were injected intraperitoneally with clodronate liposomes to deplete macrophages or an antibody to Gr-1 to deplete neutrophils. The respective controls were injected with PBS liposomes or control Ig. 24 h later, peritoneal lavage fluid cells were stained with the antibodies indicated and analyzed by flow cytometry. Data are representative of three mice in each group of WT mice, and similar results were obtained in each group of Cd300a−/− mice (Fig. 4). The survival rate after CLP was shown (n = 9 in each group. Data were pooled from two independent experiments; G and H). * P < 0.05, Student’s t test. Error bars show SD.
those that received WT BMMCs (Fig. 5, A and B), suggesting that Cd300a−/− BMMCs produced a greater amount of chemoattractants for neutrophils than did WT BMMCs in the peritoneal cavity after CLP. To directly confirm this idea, KItW-sh/W-sh mice received a 1:1 mixture of CFSE-labeled WT and Cd300a−/− BMMCs via the peritoneal cavity and were subjected to CLP. Although both WT and Cd300a−/− BMMCs transferred into the peritoneal cavity showed a low level of TNF expression, Cd300a−/− BMMCs, defined as CD300a− CFSE+ cells, showed significantly higher frequency in the BMMCs producing a high level of TNF than did WT (Cd300a+ CFSE+) BMMCs (Fig. 5 C). Together, these results indicate that CD300a inhibits production of chemoattractants for neutrophils from BMMCs in the peritoneal cavity after CLP.

Although BMMC transfer into KItW-sh/W-sh mice does not completely reconstitute the immune system in KItW-sh/W-sh mice (Dudeck et al., 2011), our results suggested that CD300a on mast cells was primarily responsible for the phenotype of prolonged survival of Cd300a−/− mice after CLP.

**Figure 5.** CD300a on mast cells is critical for survival after CLP. 
(A and B) KItW-sh/W-sh mice were injected i.p., or not injected, with BMMCs from WT or Cd300a−/− mice, and then 28 d later, CLP was performed (n = 20 in each group, data were pooled from two independent experiments) and the survival rate was shown (A). Bacterial CFUs in the peritoneal lavage fluid of mice transferred with Cd300a−/− (n = 4) and WT (n = 4) BMMCs were assayed 4 h after CLP (B). (C) KItW-sh/W-sh mice were injected i.p. with a 1:1 mixture of CFSE-labeled Cd300a−/− and WT BMMCs 24 h before CLP. CFSE-labeled cells in the peritoneal lavage fluid of mice 4 h after CLP were analyzed by flow cytometry. Data are representative of three independent experiments. *, P < 0.05, Student's t test. Error bars show SD.

**Blockade of CD300a–PS interaction prolongs survival of mice after CLP**

Because Cd300a−/− mice survived longer after CLP, we examined whether an antibody against mouse CD300a (TX41) could have a prophylactic effect on CLP-induced sepsis. TX41 does not deplete myeloid cells, including mast cells. Intrapерitoneal injection of mice with TX41 1 h before and 18 h after CLP significantly increased neutrophil numbers in the peritoneal cavity, improved bacterial clearance 4 h after CLP, and prolonged survival compared with treatment with a control antibody (Fig. 6, A–C). Similarly, intraperitoneal injection with D89E MFG-E8 also prolonged survival of WT mice compared with treatment with PBS. In contrast, D89E MFG-E8 did not change the survival of Cd300a−/− mice, indicating that D89E MFG-E8 blocked the interaction between PS and CD300a, but not other PS receptors (Fig. 6 D). Moreover, D89E MFG-E8 improved bacterial clearance of WT mice (Fig. 6 E). These results provided the formal evidence that PS on apoptotic cells affected

**Figure 6.** The blockade of the CD300a–PS interaction prolongs survival of mice after CLP. 
(A–C) WT mice were injected i.p. with 500 µg of control antibody (n = 11) or anti-Cd300a monoclonal antibody (TX41; n = 13), 1 h before and 18 h after CLP, and the survival rate is shown (A). Bacterial CFUs (B) and the numbers of neutrophils (C) in the peritoneal lavage fluid of mice (n = 5 in each group) were determined 4 h after CLP, as described. (D and E) WT or Cd300a−/− mice were injected i.p. with 50 µg D89E MFG-E8 (n = 10 and 8, respectively) or PBS (n = 9), 1 h before and 18 h after CLP, and the survival rate is shown (D). Bacterial CFUs in the peritoneal lavage fluid of mice (n = 4 in each group) were determined 4 h after CLP, as described (E). *, P < 0.05, Student’s t test. Error bars show SD. Data in A and D were each pooled from two independent experiments.
the bacterial clearance. Thus, blocking the interaction between PS and its receptor CD300a is potentially a useful therapy for prophylaxis against peritonitis-induced sepsis.

**DISCUSSION**

A large number of cells undergo apoptosis every day in physiological and pathological settings. PS receptors play a central role in engulfment of apoptotic cells and are crucial to avoiding the development of autoimmune diseases (Hanayama et al., 2004). Pathological conditions such as microbial infections significantly augment cell death by apoptosis (Hotchkiss and Nicholson, 2006) and trigger the first line of inflammatory responses by mast cells through receptors for pathogen-associated molecular patterns such as Toll-like receptors (Marshall, 2004; Bischoff, 2007; Abraham and St John, 2010). Mast cells therefore play an important role in the early phase of immunity against microbial pathogens. Our results indicate that PS not only delivers “eat-me” signals to phagocytes via PS receptors but also suppresses inflammatory responses by mast cells and macrophages via CD300a.

Although CD300a is expressed on professional phagocytes, such as macrophages and dendritic cells (Yotsumoto et al., 2003), we did not observe CD300a-mediated phagocytosis of apoptotic cells by macrophages. Because CD300a associates with SHP-1 upon ligand binding and inhibits activation signals, CD300a may not have a functional property of phagocytosis. However, it cannot be excluded that the CD300a-mediated signal suppresses, rather than augments, phagocytosis by other PS receptors such as TIM-4 (Kobayashi et al., 2007), if PS binding could be shared by CD300a and TIM-4 on a macrophage. This may depend on the binding affinity of these receptors to PS. At present, the affinity of CD300a binding to PS has remained undetermined. Very recently, Choi et al. (2011) have reported that CD300f also recognizes PS and exogenous expression of CD300f enhanced phagocytosis of apoptotic cells by fibroblast cell line L929 cells. Like CD300a, CD300f contains ITIM in the cytoplasmic portion. Upon cross-linking with antibody, the ITIM of CD300f is phosphorylated, recruits SHP-1 and SHP-2, and mediates an inhibitory signal in myeloid cells (Izawa et al., 2009). It is unclear, however, how CD300f-mediated signaling involves phagocytosis of apoptotic cells.

One of the key biological features of apoptotic cell engulfment by phagocytes is the noninflammatory nature (Fadok et al., 1998; Ravichandran and Lorenz, 2007). The molecular mechanism under this feature has still remained unclear. The suppressive effect of CD300a on the proinflammatory cytokine and chemokine production by mast cells does not necessarily account for this feature because mast cells are not phagocytes and their activation is induced by pathological conditions such as microbial infections. However, it may contribute to avoiding excessive inflammations by suppressing mast cell-mediated triggering of inflammation. Our data showed that CD300a deficiency also affected the production of both the proinflammatory and antiinflammatory cytokines TNF and IL-10, respectively, without selectivity by peritoneal resident macrophages, when these cells were cocultured with apoptotic cells in the presence of LPS. However, because SHP-1 recruitment by CD300a that is essential for CD300a-mediated inhibitory signal requires both PS binding and LPS stimulation in macrophages as well as mast cells, it is unlikely that CD300a on macrophages is involved in the noninflammatory nature of phagocytosis of apoptotic cells mediated by PS receptors other than CD300a in the physiological conditions. Further studies should be required to clarify the regulatory role of CD300a in activation of myeloid cells, including dendritic cells and neutrophils as well as mast cells and macrophages. Nonetheless, CD300a is the first PS receptor identified on mast cells and suppresses inflammatory responses by mast cells.

Sepsis, the systemic inflammatory syndrome induced by severe infections, remains a leading cause of death worldwide (Angus and Wax, 2001; Cohen, 2002). Despite extensive basic and clinical research, the pathophysiology of sepsis is still poorly understood, and trials of several therapies have failed to improve the prognosis of septic patients in large multicenter clinical trials (Riedemann et al., 2003; Russell, 2006). The best established mouse model of sepsis, CLP, has shown that mast cells play essential roles in host defense against CLP (Malaviya et al., 1996). Here, we provide compelling experimental evidence supporting the efficacy of anti-CD300a monoclonal antibody and D89E MFG-E8 adjunctive therapy for polymicrobial peritonitis-induced sepsis. Both anti-CD300a and D89E MFG-E8 blocked the binding of PS to CD300a, resulting in the increased production of chemotactants for neutrophils from mast cells induced by LPS in the peritoneal cavity. Long-term treatment with D89E MFG-E8 leads to the development of autoimmune diseases as a result of the defect of apoptotic cell clearance (Hanayama et al., 2004). However, we injected D89E MFG-E8 only twice before CLP and 18 h after CLP, which was enough for the prophylaxis of peritonitis-induced sepsis. Mast cell activation is important in the very early phase after infection, only when the blocking CD300a-mediated signaling by D89E MFG-E8 or anti-CD300a antibody should be required.

The classical function of mast cells is involved in allergic responses, in which FceRI-mediated signals lead to degranulation from mast cells (Gilfillan and Tkaczuk, 2006). In vitro analyses demonstrated that cross-linking CD300a with monoclonal antibody suppressed FceRI-mediated signals, resulting in the decreased degranulation in human and mice (Yotsumoto et al., 2003; Okoshi et al., 2005; Munitz et al., 2006; Karra et al., 2009). Because many cells undergo apoptosis at the site of allergic inflammation, CD300a may play an important role in allergic responses by mast cells and may be a potential prophylaxis and/or therapeutic target for treatment of allergic diseases.

**MATERIALS AND METHODS**

**Mice.** To construct the CD300a targeting vector, we replaced exon 1 to exon 6 of the Cd300a gene with a neomycin-resistance gene cassette (PGK-GB2-neo) using the bacterial artificial chromosome (BAC) system (Yang and Seed, 2003). BALB/c embryonic stem cells were electroporated with linearized Cd300a targeting vector, and cells were selected for G418 antibiotic resistance.
Correctly targeted embryonic stem cell clones with normal karyotypes were injected into 3.5-d-old BALB/c blastocysts to create chimeric mice (C3d00a−/−). C5d00a−/− mice were intercrossed to generate C3d00a−/− mice. Homozygous mice were obtained at the expected Mendelian frequencies and developed normally. C3d00a−/− mice and control WT mice were bred under specific pathogen-free conditions in the same room of our animal facility. C3d00a−/− deficient (C3d00a−/−) mice in the BALB/c background were backcrossed onto the C57BL/6j genetic background for 12 generations. C57BL/6j-Karb/10/14+ mice were provided by Riken BioResource Center (Tsukuba, Japan). CAD-deficient mice have been previously described (Nagata, 2005). C57BL/6j mice were purchased from Clea Japan. All experiments were performed in accordance with the guidelines of the animal ethics committee of the University of Tsukuba Animal Research Center.

**Generation of C3d00a-Fc and MFG-E8.** The fusion protein of C3d00a with the Fc portion of human IgG (C3d00a-Fc) was generated from chimeric cDNA containing the entire extracellular domain of C3d00a and the human IgG1Fc, as previously described (Tahara-Hanaoka et al., 2004). MFG-E8 cDNA containing the entire extracellular domain of CD300a and the human IgG1Fc, as previously described (Hanayama et al., 2002).

**Antibodies and cells.** Control rat antibodies and antibodies to CD11b (M1/70), F4/80, c-Kit (2B8), Gr-1 (RB6), FcεRI (MAR-1), and TNF were purchased from BD. The C3d00a-specific monoclonal antibody TX41 (rat IgG2a) was generated in our laboratory, as described previously (Yoshimoto et al., 2003). The antibody to MCP-1 was purchased from BioLegend, and the antibody to IL-13 was purchased from eBioscience. Antibodies to SHP-1 (C-19) and SHP-2 (C-18) were purchased from EMD Millipore. To generate BMMCs, 2 × 106 BM cells were cultured in a 10-cm dish in complete RPMI 1640 medium containing 10% FBS in the presence of 10 ng/ml stem cell factor and 4 ng/ml IL-3 for 3-5 wk. Cells were passaged with fresh medium every week. Flow cytometry analyses showed that >99% of the cultured cells were c-kit−/FceRI+ cells. NIH 3T3 cells were transfected with a pMX-neo retrovirus vector plasmid containing Flag-tagged C3d00a cDNA. An NIH 3T3 transfectant stably expressing TIM-4 was provided by T. Kitamura (University of Tokyo; Yamashita et al., 2010). RBL-2H3 transfectants expressing WT C3d00a and mutated C3d00a tagged with Flag at the N terminus, in which the tyrosines were replaced with phenylalanine or the cytoplasmic region was deleted, were previously described (Okoshi et al., 2005).

**Preparation of apoptotic cells and phagocytosis assay.** Thymocytes from C57BL/6 or CAD-deficient mice were incubated with 10 µM dexmethasone (Sigma-Aldrich) in RPMI medium for 6 h. Induction of apoptosis was determined by labeling PS expressed on the plasma membrane with APC-conjugated annexin V (BD) and propidium iodide (Sigma-Aldrich).

**Measurement of CFUs of aerobic bacteria.** Aerobic bacterial CFUs were quantified by plating serial dilutions of peritoneal lavage fluid and culturing them at 37°C for 48 h on brain-heart-infusion agar plates. CFUs were then enumerated by calculating the number of colonies in 1 ml peritoneal lavage fluid, as previously described (Pittas et al., 2008).

**In vivo depletion of macrophages and neutrophils.** For macrophage depletion, clodronate liposomes and control PBS liposomes (Encapsula NanoSciences) were prepared as previously described (Van Rooijen, 1989). Mice were injected i.p. with 0.5 ml liposomes 24 h before CLP. For neutrophil depletion, mice were injected i.p. with 5 µg anti-Gr-1, 24 h before CLP. WT or C3d00a−/− neutrophils (1 × 106/mice) purified from the BM were injected into some neutrophil-depleted mice just after CLP.

**RNA interference.** To target SHP-1 in BMMCs, 0.5 nM SHP-1 siRNA (sGENOME SMARTpool; Thermo Fisher Scientific) was mixed with 1 µl X-tremeGENE siRNA transfection reagent (Roche) and transfected into 5 × 105 BMMCs, as previously described (An et al., 2006). After 48 h, the supernatant was removed, and fresh medium and 0.3 mM SHP-1 siRNA were added. The cells were cultured for another 16 h before further experiments.

**Statistical analyses.** The Kaplan-Meier log-rank test was used for survival analyses. All other statistical analyses were performed using an unpaired Student’s t test. P < 0.05 was considered statistically significant.

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**REFERENCES**


