B cells mediate chronic allograft rejection independently of antibody production

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Chronic rejection is the primary cause of long-term failure of transplanted organs and is often viewed as an antibody-dependent process. Chronic rejection, however, is also observed in mice and humans with no detectable circulating alloantibodies, suggesting that antibody-independent pathways may also contribute to pathogenesis of transplant rejection. Here, we have provided direct evidence that chronic rejection of vascularized heart allografts occurs in the complete absence of antibodies, but requires the presence of B cells. Mice that were deficient for antibodies but not B cells experienced the same chronic allograft vasculopathy (CAV), which is a pathognomonic feature of chronic rejection, as WT mice; however, mice that were deficient for both B cells and antibodies were protected from CAV. B cells contributed to CAV by supporting splenic lymphoid architecture, T cell cytokine production, and infiltration of T cells into graft vessels. In chimeric mice, in which B cells were present but could not present antigen, both T cell responses and CAV were markedly reduced. These findings establish that chronic rejection can occur in the complete absence of antibodies and that B cells contribute to this process by supporting T cell responses through antigen presentation and maintenance of lymphoid architecture.

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Chronic rejection is the primary cause of long-term failure of transplanted organs and is often viewed as an antibody-dependent process. Chronic rejection, however, is also observed in mice and humans with no detectable circulating alloantibodies, suggesting that antibody-independent pathways may also contribute to pathogenesis of transplant rejection. Here, we have provided direct evidence that chronic rejection of vascularized heart allografts occurs in the complete absence of antibodies, but requires the presence of B cells. Mice that were deficient for antibodies but not B cells experienced the same chronic allograft vasculopathy (CAV), which is a pathognomonic feature of chronic rejection, as WT mice; however, mice that were deficient for both B cells and antibodies were protected from CAV. B cells contributed to CAV by supporting splenic lymphoid architecture, T cell cytokine production, and infiltration of T cells into graft vessels. In chimeric mice, in which B cells were present but could not present antigen, both T cell responses and CAV were markedly reduced. These findings establish that chronic rejection can occur in the complete absence of antibodies and that B cells contribute to this process by supporting T cell responses through antigen presentation and maintenance of lymphoid architecture.

Introduction

Chronic rejection, a late cause of long-term failure of transplanted organs, is defined by the primary cause of long-term failure of transplanted organs and is often viewed as an antibody-dependent process. Chronic rejection, however, is also observed in mice and humans with no detectable circulating alloantibodies, suggesting that antibody-independent pathways may also contribute to pathogenesis of transplant rejection. Here, we have provided direct evidence that chronic rejection of vascularized heart allografts occurs in the complete absence of antibodies, but requires the presence of B cells. Mice that were deficient for antibodies but not B cells experienced the same chronic allograft vasculopathy (CAV), which is a pathognomonic feature of chronic rejection, as WT mice; however, mice that were deficient for both B cells and antibodies were protected from CAV. B cells contributed to CAV by supporting splenic lymphoid architecture, T cell cytokine production, and infiltration of T cells into graft vessels. In chimeric mice, in which B cells were present but could not present antigen, both T cell responses and CAV were markedly reduced. These findings establish that chronic rejection can occur in the complete absence of antibodies and that B cells contribute to this process by supporting T cell responses through antigen presentation and maintenance of lymphoid architecture.

Results and Discussion

B cells are sufficient for CAV in the absence of antibodies. To study the roles of B cells and antibodies in the pathogenesis of CAV, a heterotopic allogeneic heart transplantation model was used in which acute rejection was inhibited by treating recipients with costimulation blockade (CTLA4Ig and anti-CD40L) (20). Mice that were either deficient in both B cells and antibodies (μMT) or antibodies alone (AID/μMT) were utilized as recipients. AID/μMT KO mice lack the genes encoding both secretory IgM (μs; secretory IgM) and activation-induced deaminase (AID; Aicda), and their B cells cannot undergo affinity maturation or secrete antibodies of any isotype (21). μMT mice have a targeted disruption of the immunoglobulin μ chain gene, resulting in lack of both mature B cells and secreted antibodies (22). B cell and antibody sufficient B6 (WT) mice were used as controls. All mice received BALB/c allografts, and CAV was analyzed at 100 to 110 days after transplantation. Histological examination of allografts in WT recipients revealed arteritis with perivascular inflammation and intimal hyperplasia causing obliterative vasculopathy, characteristic of CAV (Supplemental Figure 1A; supplemental material available online with this article; doi:10.1172/JCI70084). Despite the complete absence of antibodies, AID/μMT KO mice developed CAV lesions similar to those found in WT recipients (Supplemental Figure 1A). In contrast, allografts in μMT recipients, which lack both B cells and antibodies, displayed minimal CAV (Supplemental Figure 1A). Morphometric quantitation represented as percentage of vessels affected by CAV in each allograft (Figure 1A) and percentage of luminal occlusion in each vessel (Figure 1B) confirmed that CAV was attenuated in μMT but not in AID/μMT KO recipients. Importantly, CAV was restored in μMT recipients upon adoptive trans-
fer of B cells that do not produce antibodies (naive B cells from AID/μS KO, μMT, and μMT + B cells AID/μS KO recipients were transplanted with BALB/c hearts and treated with costimulation blockade (0.25 mg, CTLA4Ig and anti-CD40L, on days 2, 4, 6, and 8). μMT + B cells AID/μS KO recipients were μMT mice that received naive AID/μS KO B cells (2 × 10⁷, 2 to 4 days before transplantation). Allografts were beating and contracting at harvest (100–110 days). (A and B) Morphometric quantitation of vasculopathy in each recipient (A), and luminal occlusion in each vessel (B) (mean ± SEM; n = 26–64 vessels, 5–9 mice per group). (C) Morphometric quantitation of luminal occlusion in each vessel in Bm12 heart allografts from untreated recipients (at 90–100 days, mean ± SEM; n = 34–87 vessels, 5–10 mice per group). (D) Median fluorescence intensity of BALB/c-reactive antibodies in sera of BALB/c heart recipients at harvest (1:4 dilution, mean ± SD; n = 4–6 mice per group). *P < 0.05; **P < 0.005; ***P < 0.0005.

Figure 1

B cells are sufficient for CAV in the absence of antibodies. WT, AID/μS KO, μMT, and μMT + B cells AID/μS KO recipients were transplanted with BALB/c hearts and treated with costimulation blockade (0.25 mg, CTLA4Ig and anti-CD40L, on days 2, 4, 6, and 8). μMT + B cells AID/μS KO recipients were μMT mice that received naive AID/μS KO B cells (2 × 10⁷, 2 to 4 days before transplantation). Allografts were beating and contracting at harvest (100–110 days). (A and B) Morphometric quantitation of vasculopathy in each recipient (A), and luminal occlusion in each vessel (B) (mean ± SEM; n = 26–64 vessels, 5–9 mice per group). (C) Morphometric quantitation of luminal occlusion in each vessel in Bm12 heart allografts from untreated recipients (at 90–100 days, mean ± SEM; n = 34–87 vessels, 5–10 mice per group). (D) Median fluorescence intensity of BALB/c-reactive antibodies in sera of BALB/c heart recipients at harvest (1:4 dilution, mean ± SD; n = 4–6 mice per group). *P < 0.05; **P < 0.005; ***P < 0.0005.

Alloreactive T cell responses are diminished in the absence of B cells. To investigate whether B cells contribute to CAV by influencing T cell responses, T cell activation and cytokine production were examined at the time of graft harvest. As shown in Figure 2A, IFN-γ and TNF-α production by CD4+ and CD8+ T cells in response to donor splenocytes was intact in AID/μS KO recipients and T cell activation, measured by CD44, CD62L, and CD69 expression, was enhanced, especially in the CD8+ compartment. In contrast, cytokine production by both CD4+ and CD8+ T cells, measured as percentage and absolute number of cytokine-producing T cells, was significantly reduced in μMT recipients (Figure 2A), with evidence of diminished activation of CD4+ T cells (decreased CD44 expression). Moreover, T cell infiltration of graft vessels was conspicuous in AID/μS KO and WT recipients, but was nearly absent in μMT recipients (Figure 2B). Because B cells can affect T cell homeostasis by influencing splenic lymphoid architecture (17–19), total T cells in recipients were also enumerated. We found that CD4+ T cell numbers were normal in μMT recipients, while CD8+ T cells were slightly diminished (Figure 2C). AID/μS KO recipients, on the other hand, had a significant increase in CD4+ T cell numbers (Figure 2C). Together, these data indicate that alloreactive T cell responses are diminished in the absence of B cells. This function of B cells could be mediated indirectly by supporting splenic lymphoid architecture and/or by direct action of B cells on T cells (e.g., antigen presentation).

Cognate and noncognate functions of B cells contribute to CAV. Splenic architecture in μMT recipients was disrupted without marginal zones and diminished T cell areas (Supplemental Figure
2A) that could have accounted for attenuated alloreactive T cell responses and CAV in these mice. To test this possibility, we utilized IgHEL B cell receptor (BCR) transgenic mice wherein B cells are specific for hen egg lysozyme (HEL) (23) but do not recognize BALB/c alloantigens, and thus provide only noncognate (not dependent on recognition of antigen by B cells) functions in our transplant model. CAV was restored in Ig HEL recipients but only partially when compared with WT recipients (Figure 3A), despite preserved splenic architecture (Supplemental Figure 2B), suggesting that noncognate B cell functions alone were not sufficient. B cells in IgHEL recipients could be contributing to CAV not only by supporting lymphoid architecture but also by taking up alloantigen, albeit inefficiently, via non-BCR (noncognate) mechanisms and presenting it to T cells. It’s also possible that there is a minor contribution from the few non-HEL-specific B cells present in IgHEL recipients that could be alloreactive and present alloantigen taken up via the cognate BCR to T cells. In contrast, adoptive transfer of polyclonal AID/μS KO B cells, which provided cognate (dependent on antigen recognition by B cells) and noncognate functions but not antibodies, into μMT recipients (μMT + B cells AID/μS KO) not only improved splenic architecture (Supplemental Figure 2C), but also restored CAV to the full extent seen in WT recipients (Figure 1, A and B). μMT + B cells AID/μS KO recipients also showed greater CD4+ and CD8+ T cell IFN-γ response to donor splenocytes than IgHEL recipients (Figure 3B), suggesting that both cognate and noncognate B cell functions contributed to the alloreactive T cell response in these recipients.

To further examine the role of B cells as antigen-presenting cells in the pathogenesis of CAV, we transplanted BALB/c hearts into syngeneic BM chimeras wherein B cells were present but lacked MHC I and II expression (μMT+MHC-KO→μMT) (Supplemental Figure 3A). In these chimeras, B cells are unable to present antigen to T cells while non-B cell antigen-presenting cells remain intact. Chimeras containing B cells that can present antigen to T cells (μMT+WT→μMT) and chimeras that completely lack...
B cells (μMT→μMT) were used as controls. Although splenic architecture was preserved (Supplemental Figure 3B), CAV was attenuated in μMT+MHC-KO chimeras compared with μMT+WT chimeras and was equivalent to that observed in μMT chimeras (Figure 3C). Assessment of CD4+ and CD8+ T cell cytokines in response to donor splenocytes in chimeric mice showed a significant reduction in IFN-γ and TNF-α production in μMT+MHC-KO chimeras (Figure 3D). Finally, examination of allografts revealed vascular infiltration with CD4+ and CD8+ T cells in μMT+WT chimeras, but not in μMT+MHC-KO or μMT chimeras (Supplemental Figure 4). These findings indicate that cognate antigen presentation by B cells plays an important role in the pathogenesis of CAV by enhancing alloreactive T cell responses.

Our findings provide what we believe are new insights into the pathogenesis of chronic allograft rejection. We established that CAV could occur in the complete absence of antibodies, but not in the absence of both B cells and antibodies. We presented evidence that B cells drive the pathogenesis of CAV by supporting T cell responses through both antigen presentation and maintenance of splenic lymphoid architecture. Our findings could explain why many patients develop chronic rejection in the absence of detectable alloantibodies (3, 8). Indeed, B cell depletion abrogates CAV in primate heterotopic heart transplants, inhibits chronic rejection of murine kidney allografts, and improves survival of islet transplants in primates without necessarily eliminating donor-reactive antibodies (24–26). Similarly, B cell depletion induces disease remission in autoimmune diseases such as lupus despite persistence of autoantibodies (27).

Methods
Further information is available in Supplemental Methods.

Statistics. Two-tailed Student’s t test was used to assess statistical differences between groups using Graphpad Prism 5 software, and differences with $P < 0.05$ were considered significant.

Study approval. All animal studies were approved by the University of Pittsburgh IACUC (protocol no. 12070595; PHS assurance no. A3187-01).

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