

ORIGINAL ARTICLE

Fas mediates cardiac allograft acceptance in mice with impaired T-cell-intrinsic NF- κ B signaling

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Summary

The transcription factor NF- κ B is critical for T-cell activation and survival. We have shown that mice expressing a T-cell-restricted NF- κ B superrepressor ($\text{I}\kappa\text{B}\alpha\Delta\text{N-Tg}$) permanently accept heart but not skin allografts. Overexpression of the prosurvival factor Bcl-x_L in T cells restored heart rejection, suggesting that graft acceptance in $\text{I}\kappa\text{B}\alpha\Delta\text{N-Tg}$ mice was attributable to deletion of alloreactive T cells. *In vitro*, the increased death of $\text{I}\kappa\text{B}\alpha\Delta\text{N-Tg}$ T cells upon TCR stimulation when compared with wildtype T cells was mostly because of Fas/FasL interaction. Similarly, Fas played a key role in cardiac allograft acceptance by $\text{I}\kappa\text{B}\alpha\Delta\text{N-Tg}$ mice as both genetic and antibody-mediated inhibition of Fas-signaling restored cardiac allograft rejection. Rejection correlated with graft infiltration by T cells and splenic production of IFN- γ upon allostimulation. These results indicate that T-cell inhibition of NF- κ B results in cardiac allograft acceptance because of increased susceptibility to Fas-mediated cell death.

Introduction

T cells play a major role in acute allograft rejection. NF- κ B is a critical transcription factor for T-cell activation, proliferation and survival [1]. Regulation of NF- κ B activation is determined by the interaction between the NF- κ B dimers and their inhibitors, members of the $\text{I}\kappa\text{B}$ family. Phosphorylation of the $\text{I}\kappa\text{B}$ s induces their degradation in an ubiquitin-proteasome-dependent manner. Overexpression of a non phosphorylatable form of the inhibitor $\text{I}\kappa\text{B}\alpha$ in T cells leads to decreased NF- κ B activity, therefore impairing NF- κ B-mediated T-cell proliferation, IL-2 and IFN- γ production, and cell survival [2–4]. The latter is mostly because of the inability of NF- κ B-impaired T cells to upregulate the prosurvival factors Bcl-x_L and c-FLIP [5]. In contrast, Th2 responses remain unaffected in NF- κ B-impaired T cells [3]. Mice overexpressing the non degradable form of $\text{I}\kappa\text{B}\alpha$ selectively in their T cells ($\text{I}\kappa\text{B}\alpha\Delta\text{N-Tg}$ mice) do not develop Th1-mediated diseases, such as collagen-induced arthritis, and are also incapable of mounting an anti-parasite response against *Toxoplasma gondii* [6,7].

We have previously observed that cardiac allografts are permanently accepted in $\text{I}\kappa\text{B}\alpha\Delta\text{N-Tg}$ mice, although these animals retain the capacity to reject nonvascularized skin allografts [8]. Cardiac allograft rejection in $\text{I}\kappa\text{B}\alpha\Delta\text{N-Tg}$ mice could be restored by the overexpression in T cells of the pro-survival factor Bcl-x_L [9]. This result suggested that cardiac alloantigens were promoting apoptosis of alloreactive NF- κ B-impaired T cells, while skin allografts could surmount the NF- κ B deficiency and trigger T-cell activation. Indeed, we have found that donor Langerhans cells from the skin can significantly activate NF- κ B-impaired T cells and are sufficient to drive acute rejection of heart allografts in $\text{I}\kappa\text{B}\alpha\Delta\text{N-Tg}$ mice [10]. However, the mechanism of NF- κ B-impaired T-cell apoptosis following cardiac transplantation remained to be established.

T cells can undergo apoptosis following interactions between Fas (CD95) and FasL, TNF and TNFR1, or DR5 and TRAIL [11]. Fas mediates its effects through the activation of caspases 3 and 9, and Fas-dependent apoptosis can be prevented by expression of cFLIP [12].

T-cell receptor (TCR) stimulation results in proliferation and death of normal T cells, but susceptibility to TCR-mediated apoptosis is significantly increased in κ B α Δ N-Tg T cells [5]. This is likely because of the fact that Fas engagement results in activation of both death-inducing caspases and death-protecting NF- κ B, such that Fas-mediated NF- κ B activity limits Fas-dependent apoptosis [13]. Expression of a non functional form of Fas in κ B α Δ N-Tg T cells (Lpr/ κ B α Δ N) has been reported to protect κ B α Δ N-Tg T cells from TCR-mediated apoptosis *in vitro* [5]. These results prompted us to hypothesize that cardiac allograft acceptance in κ B α Δ N-Tg mice may be caused by unopposed Fas-mediated T-cell death among NF- κ B-impaired T cells. Our results indicate that pharmacologic or genetic inhibition of Fas restored the capacity of κ B α Δ N-Tg mice to reject cardiac allografts, promoted cardiac allograft infiltration by CD4⁺ and CD8⁺ T cells and resulted in donor-specific IFN- γ production. Therefore, Fas-mediated cell death of alloreactive T cells is necessary for cardiac allograft acceptance in mice with impaired NF- κ B signaling in T cells. These data point to T-cell-intrinsic NF- κ B and Fas as potential therapeutic targets to promote transplantation tolerance.

Materials and methods

Animals

Six- to 8-week-old C57Bl/6 (B6, H-2^b) and BALB/c (H-2^d), mice were purchased from the Jackson Laboratories (Bar Harbor, ME, USA). Mice transgenic for a T-cell-restricted κ B α super-repressor, κ B α Δ N-Tg mice, were obtained from Mark Boothby (Vanderbilt University, TE) and backcrossed to the B6 background for over 10 generations [2]. Mice deficient in Fas-signaling, Lpr (B6 background), were backcrossed to κ B α Δ N-Tg mice. Animals were housed in individually ventilated cages in a specific pathogen-free animal facility. Groups of transplanted mice were injected i.p with 500 μ g on day 0 and 250 μ g on days 2, 4 and 8 of either of anti-FasL (clone MFL4) or rat IgG (Jackson immunresearch Laboratories Inc., West Grove, PA, USA). Experiments were performed in agreement with our Institutional Animal Care and Use Committee and according to the NIH guidelines for animal use.

Antibodies

The antibodies anti-CD3 (clone 145-2C11), anti-CD28 (clone PV-1), anti-FasL (clone MFL4), anti-TNF (clone MP6-XT22) and anti-TRAIL (clone N2B2) were purified from supernatants of hybridomas following elution on a protein G column.

Cell death assays

Wildtype (WT) or κ B α Δ N-Tg splenocytes were stimulated in the presence of 1 μ g/ml of anti-CD3 mAb for 24, 48 or 72 h in the presence or absence of 10 μ g/ml each of anti-FasL, anti-TNF, anti-TRAIL, a combination of these or rat or hamster IgG. Cell death was determined by DAPI inclusion by flow cytometry.

Cytokine production assay

Splenocytes from WT or κ B α Δ N-Tg mice were stimulated with soluble anti-CD3 mAb (1 μ g/ml, clone 145-2C11). For IFN- γ ELISA, supernatants were harvested on day 5 post stimulation, and analysed by ELISA using Ab pairs, as instructed by the manufacturer (BD PharMingen, San Jose, CA, USA).

Cardiac allograft

Abdominal heterotopic cardiac transplantation was performed using a technique adapted from that originally described by Corry *et al.* [14]. Briefly, cardiac allografts were transplanted in the abdominal cavity by anastomosing the aorta and pulmonary artery of the graft end-to-side to the recipient's aorta and vena cava, respectively. The day of rejection was defined as the last day of a detectable heartbeat.

IFN- γ ELISPOTs

Splenocytes (10⁶/well) from mice transplanted 21 days earlier with BALB/c hearts and treated with rat IgG or anti-FasL mAb were stimulated with irradiated (2000 rads) B6 or BALB/c splenocytes (4 \times 10⁵/well) and incubated for 18 h in a 7% CO₂ incubator. The ELISPOT assay was conducted according to the instructions of the manufacturer (BD Biosciences, BD Pharmingen, San Jose, CA, USA), and the numbers of IFN- γ -producing spots per well were calculated using the ImmunoSpot Analyzer (CTL Analyzers LLC, Cleveland, OH, USA).

Immunohistochemistry

Grafts were removed at different time-points following transplantation, embedded with OCT (Tissue-Tek Miles Inc, Elkhart, IN, USA), and immediately frozen in liquid nitrogen. The samples were sliced into 6- μ m-thick sections at -20 °C and stained with anti-CD8 rat IgG supernatant (neat) or anti-CD4 purified rat IgG antibody as previously described [8]. Slides were evaluated under light microscopy by a pathologist blinded to the clinical rejection status of the heart. The number of CD4⁺ and

CD8⁺ cells was counted in three to four randomly chosen high-powered visual fields per section ($\times 400$ magnifications, approximately 254 mm²).

Statistical analysis

Cardiac graft mean survival time (MST), standard deviation, and *P*-values were calculated using Kaplan–Meier/log-rank test methods. Comparisons of means were performed using the Student's *t*-test or the Tukey's test for multiple comparisons, as appropriate.

Results

TNF, TRAIL and Fas participate in AICD of κ B α Δ N-Tg T cells *in vitro*

TCR stimulation induces T cells to enter the cell cycle, produce cytokines and ultimately undergo apoptosis [15]. The transcription factor NF- κ B plays a critical role in these events and particularly in cell survival, by triggering the upregulation of the pro-survival proteins IAP1/IAP2, XIAP [16] Bcl-2, Bcl-x_L, and survivin [16–19]. Consistent with the importance of NF- κ B in cell survival, TCR stimulation of κ B α Δ N-Tg splenocytes *in vitro* resulted in increased death of both CD4⁺ and CD8⁺ T cells when compared with WT T cells, as determined by DAPI-staining by flow cytometry (Fig. 1). Reduced survival of κ B α Δ N-Tg T cells was likely because of apoptosis as analysis of cell cycle progression by intracellular propidium-iodide-staining revealed an increased percentage of sub-diploid cells compared with wildtype T cells (data not shown). To determine the mechanism of cell death in κ B α Δ N T cells, WT and κ B α Δ N-Tg splenocytes were stimulated for 3 days in the presence of blocking antibodies to FasL, TNF, or TRAIL. As shown in Fig. 2, single blockade of

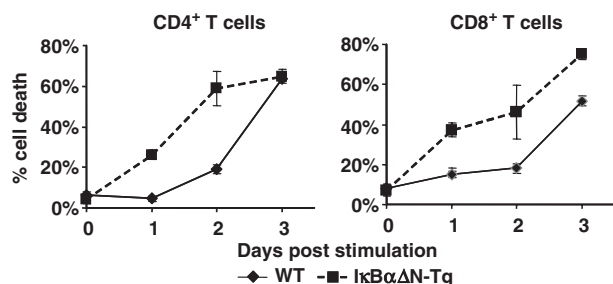


Figure 1 NF- κ B-impaired T cells have increased susceptibility to apoptosis post T-cell receptor stimulation. Wildtype or κ B α Δ N-Tg splenocytes were stimulated with 1 μ g/ml of soluble anti-CD3 mAb, and percentage of death within CD4⁺ and CD8⁺ T cells was assessed over a period of time using DAPI incorporation and flow cytometry analysis. The plot is representative of more than four independent experiments.

Fas/FasL interactions resulted in a significant reduction of TCR-induced apoptosis in WT CD4⁺ T cells and blockade of TNF or TRAIL did not have additional effects. In contrast, κ B α Δ N-Tg CD4⁺ T cells were not or weakly significantly protected from apoptosis by blockade of Fas/FasL engagement alone. However, concomitant blockade of FasL with that of TNF and TRAIL significantly reduced TCR-induced cell death of NF- κ B-impaired CD4⁺ T cells to levels similar to those observed in WT T cells, whereas no protection from cell death occurred in the absence of FasL blockade (Fig. 2). Similar data were obtained with CD8⁺ T cells (data not shown). This result suggests that Fas, TNF and TRAIL all contribute to apoptosis of NF- κ B-impaired T cells following TCR stimulation, although the role of Fas may be more important as Fas engagement can still trigger apoptosis when both TNF and TRAIL pathways are blocked. Thus, Fas may play a dominant role in apoptosis of NF- κ B-impaired T cells *in vitro*, but TNF and TRAIL also participate.

The defect in Th1 differentiation by κ B α Δ N-Tg T cells is in part Fas-dependent

Nuclear factor κ B (NF- κ B) is required for the differentiation of naïve T cells into IFN- γ -producing Th1 cells [3], and IFN- γ expression usually correlates with cardiac allograft rejection. In order to address whether Fas-mediated signals were preventing the generation of IFN- γ -producing κ B α Δ N T cells, WT or κ B α Δ N-Tg CD4⁺ T cells were stimulated and allowed to differentiate for 4 days in the presence of anti-FasL mAb or control IgG prior to restimulation with PMA and ionomycin. Upon restimulation, κ B α Δ N T cells that had differentiated in the presence of anti-FasL were able to produce more IFN- γ compared with IgG-treated control cells, although at lower levels than anti-FasL-treated wildtype T cells (Fig. 3). This result suggests that NF- κ B-impaired T cells can progress through the type 1 differentiation pathway when Fas-mediated signals are blocked.

Cardiac allograft acceptance in κ B α Δ N-Tg mice is Fas-dependent

We have previously reported that κ B α Δ N mice accept cardiac allograft on long-term basis [8]. We proposed that graft acceptance was likely because of deletion of alloreactive T cells, as cardiac allograft rejection was restored in κ B α Δ N mice that also expressed the anti-apoptotic protein Bcl-x_L in T cells [9]. In order to test whether κ B α Δ N alloreactive cells were deleted through a Fas-mediated mechanism *in vivo*, we transplanted BALB/c (H2^d) hearts into B6 (H2^b) WT, κ B α Δ N or κ B α Δ NxLpr recipient mice. Whereas all κ B α Δ N mice accepted the

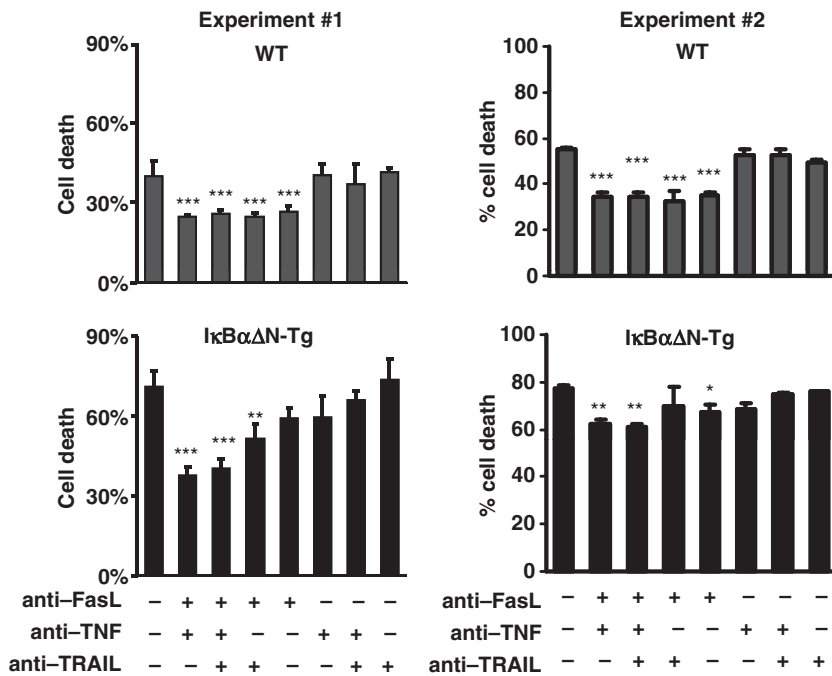


Figure 2 Blockade of Fas, TNF and TRAIL reduces T-cell receptor (TCR)-induced cell death of NF-κB-impaired T cells. Wildtype and IκBαΔN-Tg splenocytes were stimulated in the presence of 1 μg/ml of soluble anti-CD3 mAb, in the presence or absence of anti-FasL, anti-TNF, or anti-TRAIL mAbs (10 μg/ml each). Three days later cell death was assessed by DAPI incorporation in CD4⁺ cells. Two independent experiments are shown. *P < 0.05; **P < 0.01; ***P < 0.001 when compared with the untreated samples in each plot.

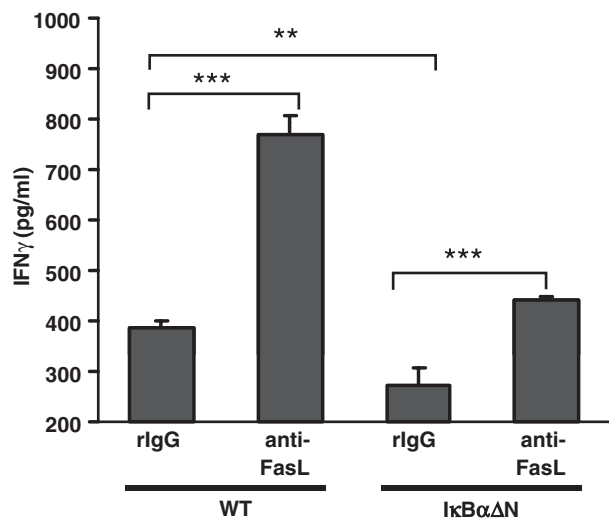


Figure 3 Blockade of Fas enhances IFN-γ production by IκBαΔN-Tg T cells *in vitro*. Wildtype and IκBαΔN-Tg splenocytes were stimulated in the presence of soluble anti-CD3 mAb (1 μg/ml), in the presence or absence of isotype control or anti-FasL mAb (10 μg/ml). Supernatants were collected at 5 days and assayed for concentration of IFN-γ by ELISA. **P < 0.01; ***P < 0.001.

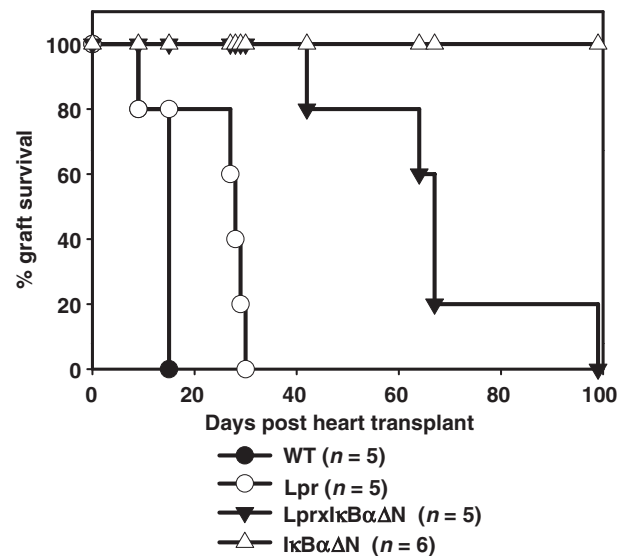


Figure 4 Genetic impairment of Fas enables heart rejection in IκBαΔN-Tg mice. IκBαΔN-Tg, Lpr or LprxIκBαΔN-Tg mice (all H-2^b) were transplanted with heterotopic BALB/c allogeneic hearts (H-2^d). Graft survival was assessed over a period of time by palpation of the beating heart. Graft mean survival time (MST): Lpr 24 ± 8; LprxIκBαΔN-Tg 67 ± 20; IκBαΔN-Tg >100.

allogeneic hearts on long-term basis, IκBαΔNxLpr mice successfully rejected cardiac allografts, although with delayed kinetics compared with WT mice (Fig. 4). To exclude that rejection in IκBαΔNxLpr mice was because of enhanced immune responses or autoimmunity triggered by the genetic absence in Fas-signaling, IκBαΔN

mice were treated with blocking anti-FasL mAb at the time of cardiac transplantation. As shown in Fig. 5a, anti-FasL treatment, but not administration of an irrelevant IgG, triggered the rejection of cardiac allografts by IκBαΔN mice, similarly to untreated WT mice, although

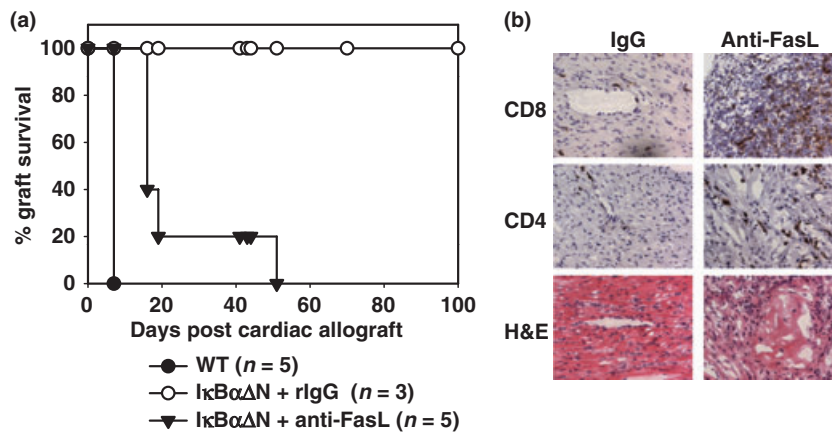


Figure 5 Blockade of Fas precipitates cardiac allograft rejection in $I\kappa B\alpha\Delta N$ -Tg mice. Wildtype or $I\kappa B\alpha\Delta N$ -Tg mice ($H-2^b$) were transplanted with BALB/c hearts ($H-2^d$) and treated with control IgG or anti-FasL mAb (500 μ g i.v. on day 0 and 250 μ g on days 2, 4 and 8). (a) Graft survival was assessed over a period of time. Graft mean survival time (MST) anti-FasL mAb: 32 ± 18 , rIgG >100 . (b) Immunohistochemistry performed on the allografts from A harvested after rejection (control IgG) or after at least 60 days (anti-FasL mAb). Presence of CD8⁺ (upper panel) or CD4⁺ (middle panel) cells was assessed in parallel to hematoxylin–eosin staining (H&E).

with slightly slower kinetics. In contrast, blockade of TNF was less effective and blockade of TRAIL showed no effect (data not shown). The anti-FasL-facilitated rejection correlated with a massive recruitment of CD4⁺ and CD8⁺ T cells into the allogeneic hearts (Fig. 5b), as also with an increase in the number of IFN- γ ⁺ cells upon restimulation of splenocytes with donor APCs (Fig. 6). These results suggest that cardiac allograft acceptance in

$I\kappa B\alpha\Delta N$ -Tg mice is attributable to apoptosis of alloreactive T cells in a Fas-dependent manner, which prevents development of IFN- γ -producing type 1 T cells.

Discussion

We have previously shown that mice with a selective impairment in T-cell-intrinsic NF- κ B activity accept cardiac allografts on long-term basis and develop donor-specific tolerance [8]. We had argued that lack of allograft rejection was likely because of deletion of alloreactive T cells because over-expression of the anti-apoptotic molecule Bcl-x_L in T cells restored rejection of heart allografts [9]. However, the mechanism by which NF- κ B-impaired alloreactive T cells underwent apoptosis following cardiac transplantation remained to be demonstrated. Our current results suggest that apoptosis of NF- κ B-impaired T cells in transplanted mice is Fas-dependent.

The importance of T-cell death as a mechanism to enable transplantation tolerance has long been recognized. This was first demonstrated by Sir Peter Medawar who showed that neonatal exposure to donor alloantigens can result in clonal deletion of alloreactive T cells and permanent acceptance of skin allografts [20]. Death of alloreactive T cells can also be achieved using myeloablation and bone marrow reconstitution to create chimerism and transplantation tolerance [21]. Conversely, mice with defects in the ability of T cells to undergo apoptosis, have been shown to be resistant to the induction of tolerance via costimulation-targeting therapies or rapamycin [22], although not in all models [23].

The role of Fas in mediating apoptosis of antigen-specific T cells was first identified following discovery of

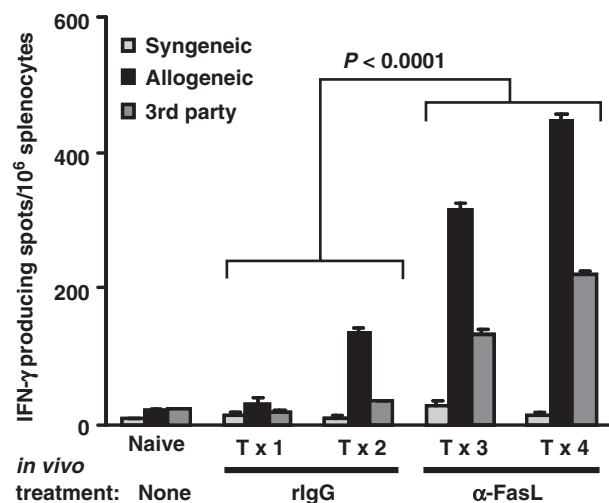


Figure 6 Blockade of Fas restores donor-specific IFN- γ production in transplanted $I\kappa B\alpha\Delta N$ -Tg mice. $I\kappa B\alpha\Delta N$ -Tg mice were transplanted with BALB/c cardiac allografts and treated with anti-FasL or rat IgG as shown in Fig. 5. On day 21 post-transplantation (Tx), splenocytes were harvested and stimulated with syngeneic (B6), allogeneic (BALB/c) or third party (C3H, $H-2^k$) irradiated splenocytes for 24 h. The frequency of IFN- γ -producing cells was assessed by ELISPOT. Tx1-4 correspond to individual animals.

expression of FasL by parenchymal cells from immune-privileged sites such as the anterior chamber of the eye or the testes [24]. Several groups have attempted to mimic this physiologic situation for therapeutic purposes, by genetically engineering tissues to express FasL and thus destroy infiltrating T cells that express active Fas. In pancreatic islets, this was counterproductive as it resulted in β -cell destruction by fratricide because β cells also express Fas [25]. However, this approach has proven more successful upon transplantation of FasL-transduced allogeneic chondrocytes in pigs [26] or using injection of donor splenocytes engineered to express FasL in a model of cardiac transplantation in rats [27]. Another recent approach has been to generate killer artificial APCs, using beads coated with anti-Fas antibody together with HLA-A2-Ig dimers. These beads result in the deletion of HLA-A2-specific human T cells in a Fas-dependent manner [28]. Our results indicate that selective inactivation of T-cell-intrinsic NF- κ B also facilitates Fas-dependent apoptosis of alloreactive T cells.

In addition to Fas, other death domain-containing receptors have been shown to play a role in T-cell apoptosis. These include TNFR and TRAIL [29,30]. The TRAIL/DR5 pathway in particular has recently been identified as a critical mechanism by which CD4⁺FoxP3⁺ regulatory T cells (Tregs) mediate apoptosis of CD4⁺ conventional T cells and Tregs failed to enhance survival of skin allografts in the presence of blocking anti-DR5 antibody [31]. However, blockade of TNF and TRAIL had little impact on cardiac allograft acceptance by I κ B α Δ N-Tg mice (data not shown). This may be because Tregs do not appear to play a role in transplantation tolerance in I κ B α Δ N-Tg mice, as these mice did not display increased numbers of Tregs, increased suppressor function by Tregs or increased susceptibility of conventional T cells to suppression by Tregs [9].

Our results show that blockade of Fas resulted in increased recovery of IFN- γ -producing cells *in vitro* and increased frequency of IFN- γ -secreting alloreactive I κ B α Δ N-Tg T cells *in vivo*. This is consistent with the fact that Th1 cells that make IFN- γ and IL-2 are more susceptible to Fas-mediated apoptosis than Th2 cells that produce IL-4 [32]. It is interesting to note that I κ B α Δ N-Tg T cells are known to have defects in Th1 differentiation [3], clonal expansion and IFN- γ gene activation [33]. Our results of recovered IFN- γ production by I κ B α Δ N-Tg T cells upon Fas/FasL blockade suggest that one of the main reasons why NF- κ B-impaired T cells fail to become Th1 cells *in vivo* is Fas-signaling. It is noteworthy that blockade of the Fas/FasL pathway resulted in as much IFN- γ production by I κ B α Δ N-Tg T cells as by isotype control-treated wildtype cells (see Fig. 3) despite increased apoptosis of the anti-FasL-treated NF- κ B-impaired T cells

compared with the IgG-treated wildtype cells (see Fig. 2). This may be because of a slight increase in IFN- γ production on a per cell basis as determined by intracellular staining (data not shown) or to the ability of the NF- κ B-impaired T cells to differentiate and produce IFN- γ prior to their apoptosis.

Histologic analysis of rejecting cardiac allografts from I κ B α Δ N-Tg mice treated with anti-FasL mAb revealed infiltration by both CD4⁺ and CD8⁺ T cells suggesting a role for both T-cell subsets in acute rejection of donor hearts. Although cardiomyocytes do not express MHC class II, donor dendritic cells that express class II have been recently identified in cardiac valves and aortic root [34]. Furthermore, expression of class II by donor hearts but not recipient mice is known to be sufficient for rejection of cardiac allografts by adoptively transferred CD4⁺ T cells [35]. These data suggest that direct recognition of alloantigen by a subset of CD4⁺ T cells can mediate acute rejection of heart allografts despite low MHC class II expression. Although CD4⁺ but not CD8⁺ T cells are necessary and sufficient for rejection of cardiac allografts, CD8⁺ T cells are usually more abundantly found in rejecting heart transplants and become essential for cardiac allograft rejection if the function of CD4⁺ T cells is impaired such as in CD28-deficient mice [36]. Whether CD8⁺ T cells are essential for rejection in anti-FasL-treated I κ B α Δ N-Tg mice in which T-cell function is also reduced remains to be demonstrated.

In addition to its role in mediating apoptosis of T cells, Fas has been shown to play a role in allograft cells' death. For instance, expression of both perforin and FasL by CD8⁺ T cells was recently shown to be important for the rejection of islet allografts [37]. However, blockade of Fas/FasL interactions in our model promoted rather than prevented rejection of cardiac allografts in I κ B α Δ N-Tg mice, suggesting that other cytotoxic pathways can mediate destruction of cardiac allografts in the absence of Fas. This is consistent with a previous report demonstrating that cardiac allograft acceptance could still occur in gld mice that lack expression of FasL in all recipient cells and therefore can not engage Fas on graft cells [38].

In summary, our data show that the mechanism by which inhibition of T-cell-intrinsic NF- κ B activation leads to tolerance following cardiac transplantation is via Fas-mediated apoptosis of NF- κ B-impaired T cells. Our results support development of T-cell-specific NF- κ B inhibitors or of T-cell-specific Fas-agonistic drugs for use in clinical transplantation.

Authorship

LL Molinero co-designed, performed or supervised all experiments and co-wrote manuscript, Y Wang and P

Zhou transplanted the allografts, H. Yagita contributed important reagents, ML Alegre co-designed the experiments and co-wrote the manuscript.

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References

- Alegre ML. Targeting NF- κ B in the immune system to prevent acute allograft rejection. *Curr Opin Organ Transplant* 2004; **9**: 252.
- Boothby MR, Mora AL, Scherer DC, *et al.* Perturbation of the T lymphocyte lineage in transgenic mice expressing a constitutive repressor of nuclear factor (NF)- κ B. *J Exp Med* 1997; **185**: 1897.
- Aronica MA, Mora AL, Mitchell DB, *et al.* Preferential role for NF- κ B/Rel signaling in the type 1 but not type 2 T cell-dependent immune response in vivo. *J Immunol* 1999; **163**: 5116.
- Hettmann T, DiDonato J, Karin M, *et al.* An essential role for nuclear factor κ B in promoting double positive thymocyte apoptosis. *J Exp Med* 1999; **189**: 145.
- Mora AL, Corn RA, Stanic AK, *et al.* Antiapoptotic function of NF- κ B in T lymphocytes is influenced by their differentiation status: roles of Fas, c-FLIP, and Bcl-xL. *Cell Death Differ* 2003; **10**: 1032.
- Seetharaman R, Mora AL, Nabozny G, *et al.* Essential role of T cell NF- κ B activation in collagen-induced arthritis. *J Immunol* 1999; **163**: 1577.
- Tato CM, Villarino A, Caamano JH, *et al.* Inhibition of NF- κ B activity in T and NK cells results in defective effector cell expansion and production of IFN- γ required for resistance to *Toxoplasma gondii*. *J Immunol* 2003; **170**: 3139.
- Zhou P, Hwang KW, Palucki DA, *et al.* Impaired NF- κ B activation in T cells permits tolerance to primary heart allografts and to secondary donor skin grafts. *Am J Transplant* 2003; **3**: 139.
- Zhou P, Balin SJ, Mashayekhi M, *et al.* Transplantation tolerance in NF- κ B-impaired mice is not due to regulation but is prevented by transgenic expression of Bcl-xL. *J Immunol* 2005; **174**: 3447.
- Molinero L, Zhou P, Wang Y, *et al.* Epidermal Langerhans cells play a major role in skin allograft rejection in mice with NF- κ B-impaired T cells. *Am J Transplant* 2008; **8**: 21.
- Zhou T, Mountz JD, Kimberly RP. Immunobiology of tumor necrosis factor receptor superfamily. *Immunol Res* 2002; **26**: 323.
- Thorburn A. Death receptor-induced cell killing. *Cell Signal* 2004; **16**: 139.
- Legembre P, Barnhart BC, Zheng L, *et al.* Induction of apoptosis and activation of NF- κ B by CD95 require different signalling thresholds. *EMBO Rep* 2004; **5**: 1084.
- Corry RJ, Winn HJ, Russell PS. Primarily vascularized allografts of hearts in mice. The role of H-2D, H-2K, and non-H-2 antigens in rejection. *Transplantation* 1973; **16**: 343.
- Sica A, Dorman L, Viggiano V, *et al.* Interaction of NF- κ B and NFAT with the interferon- γ promoter. *J Biol Chem* 1997; **272**: 30412.
- Stehlik C, de Martin R, Kumabashiri I, *et al.* Nuclear factor (NF)- κ B-regulated X-chromosome-linked iap gene expression protects endothelial cells from tumor necrosis factor α -induced apoptosis. *J Exp Med* 1998; **188**: 211.
- Chu ZL, McKinsey TA, Liu L, *et al.* Suppression of tumor necrosis factor-induced cell death by inhibitor of apoptosis c-IAP2 is under NF- κ B control. *Proc Natl Acad Sci U S A* 1997; **94**: 10057.
- Tamatani M, Che YH, Matsuzaki H, *et al.* Tumor necrosis factor induces Bcl-2 and Bcl-x expression through NF- κ B activation in primary hippocampal neurons. *J Biol Chem* 1999; **274**: 8531.
- Song J, So T, Croft M. Activation of NF- κ B1 by OX40 contributes to antigen-driven T cell expansion and survival. *J Immunol* 2008; **180**: 7240.
- Billingham RE, Brent L, Medawar PB. Activity acquired tolerance to foreign cells. *Nature* 1953; **172**: 602.
- Wekerle T, Sykes M. Mixed chimerism as an approach for the induction of transplantation tolerance. *Transplantation* 1999; **68**: 459.
- Wells AD, Li XC, Li Y, *et al.* Requirement for T-cell apoptosis in the induction of peripheral transplantation tolerance. *Nat Med* 1999; **5**: 1303.
- Lehnert AM, Murray-Segal L, Cowan PJ, *et al.* Blockade of the passive cell death pathway does not prevent tolerance induction to islet grafts. *Transplantation* 2007; **83**: 653.
- Griffith TS, Brunner T, Fletcher SM, *et al.* Fas ligand-induced apoptosis as a mechanism of immune privilege. *Science* 1995; **270**: 1189.
- Kang SM, Schneider DB, Lin Z, *et al.* Fas ligand expression in islets of Langerhans does not confer immune privilege and instead targets them for rapid destruction. *Nat Med* 1997; **3**: 738.
- Xie GH, Wang SJ, Wang Y, *et al.* Fas Ligand gene transfer enhances the survival of tissue-engineered chondrocyte allografts in mini-pigs. *Transpl Immunol* 2008; **19**: 145.
- Yolcu ES, Gu X, Lacelle C, *et al.* Induction of tolerance to cardiac allografts using donor splenocytes engineered to display on their surface an exogenous fas ligand protein. *J Immunol* 2008; **181**: 931.

28. Schutz C, Fleck M, Mackensen A, *et al.* Killer artificial antigen-presenting cells: a novel strategy to delete specific T cells. *Blood* 2008; **111**: 3546.
29. Holtzman MJ, Green JM, Jayaraman S, *et al.* Regulation of T cell apoptosis. *Apoptosis* 2000; **5**: 459.
30. Li X, McKinstry KK, Swain SL, *et al.* IFN-gamma acts directly on activated CD4+ T cells during mycobacterial infection to promote apoptosis by inducing components of the intracellular apoptosis machinery and by inducing extracellular proapoptotic signals. *J Immunol* 2007; **179**: 939.
31. Ren X, Ye F, Jiang Z, *et al.* Involvement of cellular death in TRAIL/DR5-dependent suppression induced by CD4(+)CD25(+) regulatory T cells. *Cell Death Differ* 2007; **14**: 2076.
32. Zhang X, Brunner T, Carter L, *et al.* Unequal death in T helper cell (Th)1 and Th2 effectors: Th1, but not Th2, effectors undergo rapid Fas/FasL-mediated apoptosis. *J Exp Med* 1997; **185**: 1837.
33. Corn RA, Aronica MA, Zhang F, *et al.* T cell-intrinsic requirement for NF-kappa B induction in postdifferentiation IFN-gamma production and clonal expansion in a Th1 response. *J Immunol* 2003; **171**: 1816.
34. Choi JH, Do Y, Cheong C, *et al.* Identification of antigen-presenting dendritic cells in mouse aorta and cardiac valves. *J Exp Med* 2009; **16**: 16.
35. Pietra BA, Wiseman A, Bolwerk A, *et al.* CD4 T cell-mediated cardiac allograft rejection requires donor but not host MHC class II. *J Clin Invest* 2000; **106**: 1003.
36. Szot GL, Zhou P, Rulifson I, *et al.* Different mechanisms of cardiac allograft rejection in wildtype and CD28-deficient mice. *Am J Transplant* 2001; **1**: 38.
37. Sleater M, Diamond AS, Gill RG. Islet allograft rejection by contact-dependent CD8+ T cells: perforin and FasL play alternate but obligatory roles. *Am J Transplant* 2007; **7**: 1927.
38. Wagener ME, Konieczny BT, Dai Z, *et al.* Alloantigen-driven T cell death mediated by Fas ligand and tumor necrosis factor-alpha is not essential for the induction of allograft acceptance. *Transplantation* 2000; **69**: 2428.