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Long-Term Heart Transplant Survival by Targeting the Ionotropic Purinergic Receptor P2X7

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Abstract

Background—Heart transplantation is a lifesaving procedure for patients with end-stage heart failure. Despite much effort and advances in the field, current immunosuppressive regimens are still associated with poor long-term cardiac allograft outcomes as well as with the development of complications including infections and malignancies. The development of a novel, short-term and effective immunomodulatory protocol will thus be an important achievement. The purine adenosine 5′-triphosphate (ATP), released during cell damage/activation, is sensed by the ionotropic purinergic receptor P2X7 (P2X7R) on lymphocytes and regulates T cell activation. Novel clinical-grade P2X7R inhibitors are available, rendering the targeting of P2X7R a potential therapy in cardiac transplantation.

Methods and Results—We analyzed P2X7R expression in patients and mice and P2X7R targeting in murine recipients in the context of cardiac transplantation. Our data demonstrate that P2X7R is specifically upregulated in graft-infiltrating lymphocytes in cardiac-transplanted humans and mice. Short-term P2X7R targeting with periodate-oxidized ATP (oATP) promotes long-term cardiac transplant survival in 80% of murine recipients of a fully mismatched allograft. Long-term survival of cardiac transplants was associated with reduced T cell activation, Th1/Th17 differentiation and inhibition of STAT3 phosphorylation in T cells, thus leading to a reduced transplant infiltrate and coronaropathy. *In vitro* genetic upregulation of the P2X7R pathway was also shown to stimulate Th1/Th17 cell generation. Finally, P2X7R targeting halted the progression of coronaropathy in a murine model of chronic rejection as well.

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Conflict of Interest Disclosures: None.

Conclusions—P2X7R targeting is a novel clinically relevant strategy to prolong cardiac transplant survival.

Keywords

Transplantation; rejection; P2X7R; immunology

INTRODUCTION

Heart transplantation is a lifesaving procedure for patients with end-stage heart failure[1, 2]; however, despite much improvement in surgical approaches and patient management, the late outcome of graft survival has not improved in the last decade[2, 3]. While current immunosuppressive regimens have brought about a drastic reduction in acute rejection episodes[3], the rate of chronic rejection leading to cardiac transplant loss has not improved, and the risk of immunosuppression-related graft toxicity, cancer, infections and coronary allograft vasculopathy remains high[2–4]. Thus, in order to improve transplantation outcomes and lessen the need for lifelong immunosuppression, it is critical to continue the development of novel immunomodulatory strategies to promote stable graft acceptance[5]. The alloimmune response involves complex immunological interactions between inflammatory mechanisms, which cause graft rejection, and anti-inflammatory mechanisms, which promote tolerance of the graft[6]. Blocking pathogenic and/or upregulating tolerogenic mechanisms has been shown to result in enhanced graft survival[7]. In order to achieve complete activation of T cells during the alloimmune response, delivery of signal 1 (engagement of the TCR with the MHC-peptide complex on antigen-presenting cell [APCs]) and signal 2 (interaction of costimulatory molecules) is required[8, 9]. However, other players, including innate immunity and inflammation, have been recently recognized to exert a major role[10, 11]. The purine adenosine 5′-triphosphate (ATP), released during cell damage/inflammation, may serve as one such signal. ATP is present at high concentrations within the cells[12], and it is thus released following cell damage or death[13]; moreover, ATP can be secreted by immune cells following activation[14, 15]. ATP is abundant at sites of inflammation and is sensed by ionotropic purinergic P2X receptors (7 receptors named P2X1R-P2X7R, or P2XsR)[16–18]. P2XsR have been associated *in vitro* to T cell activation and IL-2 production[14, 19–21] and *in vivo* to graft-versus-host disease[18]. Recently, ATP has been shown to play a major role in Th17 differentiation[22] and Treg inhibition[23], and Th1 and Th17 immune responses have been associated with organ rejection[24, 25]. Indeed, natural ATP/P2XsR inhibitors with the ability to hydrolyze ATP are expressed on the cellular plasma membrane (e.g. the ectonucleotidases CD39 and CD73)[26]. Novel P2X7R inhibitors are available for human use, including periodate-oxidized ATP (oATP), CE224,535, AZD9056 and GSK1482160, thereby rendering P2X7R targeting a potential path to be tested in transplantation[27]. oATP, a small Schiff base molecule, is an irreversible antagonist of P2X7R due to the selective modification of lysine residues that occurs in the vicinity of the ATP-binding site[28]; oATP has been also proposed to exert additional inhibitory effect on the other purinergic receptors[20]. We aim to unveil the largely unknown role of P2X7R in heart transplantation and to target the ionotropic purinergic receptor P2X7R in order to achieve tolerance towards cardiac transplants.

MATERIALS AND METHODS

Immunological Methods can be found in Online Supplemental Materials.

Patients

Cardiac samples were obtained from the right side of the interventricular septum of cardiac transplant recipients at Niguarda Ca' Granda Hospital, Milan, Italy. Samples were formalin-

fixed, paraffin-embedded, sectioned, and histologically graded by a cardiac pathologist according to the 2005 ISHLT criteria[29]. Characteristics of patients and immunosuppressive regimen[30] are depicted in Table 1.

Mice

C57BL/6, BALB/c, C57BL/6 P2X7$^{-/-}$, B6.C-H2^{bm12} (bm12), and C57BL/6 Rag1$^{-/-}$ mice of various ages were obtained from the Jackson Laboratory, Bar Harbor, Maine. ABM TCR-Tg mice have been described previously[31] and were maintained as a breeding colony in our animal facility. All mice were cared for and used in accordance with institutional guidelines. Protocols were approved by the Harvard Medical School Animal Care and Use Committee.

Interventional studies

Mice were injected i.p. with oATP (Medestea srl, Turin, Italy) 250 μg/day i.p. for 14 days and Colivelin (Tocris, Minneapolis, MN) 7 nM/day for 7 days. *In vitro* assays were performed in the presence of varying concentrations of oATP, NF-449 (P2X1R inhibitor), and 5-BDBD (P2X4R inhibitor) from Tocris Bioscience (Bristol, UK)

Heart transplantation

Vascularized cardiac allografts were transplanted intra-abdominally using microsurgical techniques as described by Corry et al.[32]. Rejection was determined as complete cessation of cardiac contractility and was confirmed by direct visualization.

Histology and immunohistochemistry

Immunohistochemistry was performed with 5-micron-thick formalin-fixed, paraffin-embedded tissue section. Photomicrographs (400x) were taken using an Olympus BX41 microscope (Center Valley, PA). The following primary antibodies were used: anti-Mac2, anti–CD3 (Cell Marque, Rocklin, CA), anti-CD20, anti CD68 (Dako, Glostrup, Denmark), and anti-P2X7 (Alomone Labs, Jerusalem, Israel). As isotype control for anti-P2X7R, normal Rabbit IgG (R&D Systems, Minneapolis, MN) was used. Graft histology was evaluated by an expert pathologist and was quantified as follows: *(i) Heart coronary vasculopathy*: 0: normal arteries, 1: mild arterial wall infiltration, 2: heavy arterial wall infiltration with partial luminal occlusion, 3: complete luminal occlusion; *(ii) Heart cell infiltrate*: 0: no cell infiltrate, 1: mild cell infiltrate, 2: medium cell infiltrate, 3: heavy cell infiltrate.

Confocal microscopy

Immunofluorescence samples were observed using a confocal system (LSM 510 Meta scan head integrated with the Axiovert 200 M inverted microscope; Carl Zeiss, Jena, Germany) with a 63x oil objective. Images were acquired in multitrack mode, using consecutive and independent optical pathways.

Quantitative real-time PCR

RNA was purified using an RNeasy kit (Qiagen, Valencia, CA) and was reverse-transcribed into cDNA using Superscript III (Invitrogen, Carlsbad, CA). Transcripts were amplified using a 7300 Real-Time PCR System (Applied Biosystems, Foster City, CA); primers were obtained from Applied Biosystems. QPCR products were normalized to copies of GAPDH.

Flow cytometry and intracellular cytokine staining

Annexin V Apoptosis Detection Kit, anti-mouse CD4, CD8, CD25, CD44, CD62L, IFN-γ, IL-17, and FoxP3, were purchased from BD Biosciences and eBioscience (San Diego, CA), anti-mouse P2X7 was purchased from Alomone Labs[33].

Phoshoprotein determination

Cells were lysed using 30 μL of Lysis Buffer provided with the Millipore MILLIPLEX® MAP kit (Millipore, Billerica, MA) supplemented with protease inhibitor. The Millipore MILLIPLEX® MAP Cell Signaling Assay and the Luminex xMAP platform was used according to the manufacturer's protocol (Millipore).

Western blot

Total protein concentration in cell lysates was measured using a Bradford assay (Bio-rad, Hercules, CA). Proteins were resolved on an SDS polyacrylamide gel via electrophoresis and were transferred to a nitrocellulose membrane and then incubated with primary rabbit anti-P2X1, anti-P2X4, and anti-P2X7 receptor antibodies (Alomone Labs), anti-T-bet/Tbx21 and anti-ROR- γ(Abcam, Cambridge, MA), anti-Stat3 and anti-Phospho Stat3 (Ser727) (Cell Signaling, Danvers, MA) as well as GAPDH (Cell Signaling). Densitometric quantification of band intensity was analyzed using ImageJ software and was normalized to GAPDH loading control expression.

Statistical analysis

Data are expressed as means±standard error of mean. Statistical differences in survival times were determined by the use of Kaplan-Meier curves, followed by the log-rank test. Analyses were performed in SAS (SAS Institute, Cary, NC, v. 9.3). All data were transformed to their base 10 logarithms for their statistical evaluation. Levene's test was used to test homogeneity of variances. Whenever unequal variances existed in the comparison of 3 groups or more, Welch's ANOVA with appropriate degrees (≥2) of freedom was used to compare the groups. Subsequently, post hoc analysis of Welch T test with Bonferoni correction was applied. In the two group comparison, Levene's test and Welch T test were used. $P < 0.05$ was considered significant. Graphs were generated using GraphPad Prism version 5.0 (GraphPad Software, San Diego, CA).

RESULTS

P2X7R is induced in cardiac transplants during the alloimmune response

We evaluated the expression of P2XsR in cardiac transplants *in vivo*. Hearts from BALB/c (H-2^d) mice were heterotopically transplanted into C57BL/6 (H-2^b) mice, and cardiac transplants and splenocytes were harvested at day 7 after transplantation (the average time for cardiac transplant rejection). Expression of the P2XsR was compared to baseline values (i.e. untransplanted BALB/c hearts or naïve C57BL/6 splenocytes) by real-time PCR. Upregulation of P2X1R (14-fold increase), P2X4R (4-fold increase) and P2X7R (9-fold increase) receptors was observed in the cardiac transplants (Figures 1A, 1D and 1G). Conversely, no induction of P2XsR was observed in splenocytes of cardiac-transplanted mice (data not shown). To dissect the specific effect of the alloimmune response from effects of ischemia-reperfusion injury and nonspecific inflammation, we compared P2XsR expression in allografts and syngrafts (C57BL/6 hearts into C57BL/6 recipients). P2X1R, P2X4R and P2X7R were also upregulated in syngeneic heart transplants compared to baseline (Figures 1A, 1D and 1G); however only P2X7R was significantly increased in allogeneic compared to syngeneic transplants (Figure 1G). P2X2R, P2X3R, P2X5R and P2X6R (Figures 1B, 1C, 1E, and 1F) expression was unchanged in both cardiac syngrafts

and allografts compared to baseline. We then assessed which cell type was responsible for the P2X7R upregulation observed using immunohistochemical analysis. P2X7R staining was negative in untransplanted BALB/c hearts (data not shown), while clear positive staining was evident in the mononuclear immune cell infiltrate of cardiac transplants harvested at day 7 (Figures 1H1 and 1H2); cardiomyocytes and other parenchymal cells appeared to be negative for P2X7R staining. We also confirmed complete overlap between $CD3^+$ T cells and P2X7R expression via immunofluorescence and confocal microscopy (Figures 1I1–1I3). We additionally evaluated whether P2X7R upregulation was a phenomenon present in patients (Table 1). When we analyzed the graft infiltrate in patients suffering from acute heart rejection, clear expression of P2X7R was observed (Figures 1J1 and 1J2), and confocal imaging confirmed that P2X7R staining overlapped with CD3 staining (Figures 1K1, 1K2 and1K3). No colocalization was evident between P2X7R expression and $CD20^+$ B cells (L) or $CD68^+$ macrophages (M).

In vivo short-term P2X7R targeting prevents cardiac transplant rejection, abrogates the Th1/Th17 immune response and reduces effector T cells in mice

We next tested the effect of P2X7R targeting in preventing cardiac transplant rejection using the P2X7R inhibitor oATP. Untreated C57BL/6 mice transplanted with BALB/c hearts (fully mismatched) invariably rejected grafts within 7 days (mean survival time [MST] of 7 days; Figure 2A). P2X7R targeting using short-term treatment of oATP (250 mg oATP i.p. daily for 14 days) induced long-term cardiac transplant survival (>100 days) in 80% of recipients (Figure 2A). To evaluate the effect of P2X7R targeting on the immune system of cardiac-transplanted mice, splenocytes were harvested at days 7 and 100 post-transplantation and were challenged with BALB/c irradiated splenocytes in an ELISPOT assay. Reduced numbers of IFN-γ-producing cells (Figure 2B) and increased numbers of IL-4-producing cells (Figure 2C) were observed in oATP-treated compared to untreated mice at day 7, with a stronger effect observed at day 100 in oATP-treated mice (Figures 2B and 2C). The percentages of peripheral $CD4^+$ effector T cells ($CD4^+CD44^{hi}CD62L^{low}$, or $CD4^+$ Teffs), $CD8^+$ effector T cells ($CD8^+CD44^{hi}CD62L^{low}$,or $CD8^+$ Teffs), regulatory T cells ($CD4^+CD25^+FoxP3^+$, or Tregs) and Th17 cells ($CD4^+IL17^+$) were quantified in cardiac-transplanted mice by flow cytometric analysis. The percentages of $CD4^+$ Teffs (Figure 2D) and $CD8^+$ Teffs (Figure 2E) were reduced by *in vivo* short-term P2X7R targeting in mice at days 7 and 100 post-transplantation compared to untreated mice. The percentage of Th17 cells was similarly reduced (Figure 2F). No differences in the percentage of Tregs were observed between treated and untreated mice at day 7, but an increase was observed at day 100 (Figure 2G). Thus, we show that short-term P2X7R targeting reshapes the immune system and induces hyporesponsiveness toward donor antigens.

In vivo short-term P2X7R targeting induces anergy towards donor-derived alloantigens but preserves immunocompetence in cardiac-transplanted mice

To assess whether long-term cardiac transplant survival was associated with active regulation towards alloantigens or with reduced immunocompetence, hearts from BALB/c mice were transplanted into immunodeficient C57BL/6 $Rag^{-/-}$ mice together with splenocytes obtained from cardiac transplant recipients. Graft rejection was observed within 20 days in mice adoptively transferred with naïve C57BL/6 splenocytes, and no protection was observed when splenocytes obtained from mice with long-term graft function were co-adoptively transferred with naïve splenocytes (Figure 2H). Conversely, prolonged graft survival greater than 50 days was observed when splenocytes obtained from cardiac-transplanted mice with long-term graft function were adoptively transferred (Figure 2H). These data suggest that *in vivo* short-term P2X7R targeting is more likely to induce anergy toward graft antigens than to induce active regulation. We then tested the immunocompetence of treated mice at day 100 after transplantation. Naïve C57BL/6 mice or

oATP-treated mice were immunized with ovalbumin, and splenocytes were rechallenged *in vitro* 7 days later; no differences in numbers of IFN-γ-producing cells were observed (Figure 2I). These data demonstrate that *in vivo* short-term P2X7R targeting promotes anergy toward graft antigens while maintaining immunocompetence.

In vivo short-term P2X7R targeting reduces infiltration and Th1/Th17 transcripts in cardiac transplants

To further investigate the effect of *in vivo* short-term P2X7R targeting on the anti-graft response, we analyzed cardiac transplant infiltrate in oATP-treated and untreated mice. Histological analysis performed at day 7 post-transplantation revealed a reduced $CD3^+$ T cell infiltrate in treated (Figures 3B1 and 3B2) compared to untreated mice (Figures 3A1 and 3A2), and semi-quantitative analysis confirmed a reduction in degree of infiltration and of coronary vasculopathy (Figures 3C and 3D). To investigate the effect of oATP treatment on Th1 and Th17 cells infiltrating the cardiac transplant, we analyzed allograft mRNA expression of T-bet (a Th1 cell marker) and of ROR-γ (a Th17 cell marker); both markers appeared substantially reduced in oATP-treated mice (Figures 3E and 3F), while no difference in the Th2 transcript GATA3 was observed (data not shown). At day 100, cardiac allografts were well-preserved and free from infiltration in oATP-treated mice (Figures 3G1 and 3G2). Thus, pathological analysis confirms that P2X7R targeting preserves cardiac transplant morphology.

In vivo short-term P2X7R targeting inhibits the expansion of alloantigen-specific T cells

To address whether the inhibition of the effector T cell compartment is related to reduced priming and expansion of alloreactive T cells or to their increased apoptosis, we tracked alloreactive-specific T cells in a transgenic model of cardiac transplantation. Bm12 hearts were transplanted into C57BL/6 $Rag^{-/-}$ mice, and 3×10^6 ABM $CD4^+$ TCR-Tg T cells (specific for bm12 MHC class II antigens) were subsequently adoptively transferred into cardiac transplant recipients[31]. Seven days post-transplantation, reduced numbers of ABM $CD4^+$ TCR-Tg T cells were evident in oATP-treated compared to untreated mice (Figure 4A). A marked reduction in the numbers of Teffs and Th17 cells within the Tg population was also observed in oATP-treated compared to untreated mice (Figures 4B and 4C, respectively). We then examined whether the reduced number of alloantigen-specific $CD4^+$ T cells was due to reduced proliferation or to increased apoptosis. A decrease in ABM $CD4^+$ TCR-Tg T cell proliferation, as assessed by the dilution of the intracellular dye CFSE, was observed in oATP-treated (Figure 4E) compared to untreated mice (Figure 4D), without substantial differences in TCR-Tg T cell apoptosis 4 days following adoptive transfer (Figures 4F and 4G). The results obtained demonstrate that the inhibition of the effector cell compartment upon oATP treatment is not mediated by a significant increase in apoptosis but rather to decreased proliferation.

P2X7R is required for oATP to prolong cardiac transplant survival

oATP has been proposed to exert secondary immunomodulatory mechanisms, primarily related to the inhibition of the remaining P2XsR[20]. To verify that the effect on the prevention of cardiac transplant rejection was predominantly due to P2X7R inhibition, we made use of the $P2X7R^{-/-}$C57BL/6 mouse model. BALB/c hearts were transplanted into $P2X7R^{-/-}$ mice, and cardiac transplant survival was compared to that of wild-type recipients. A significant prolongation of cardiac transplant survival was observed in $P2X7R^{-/-}$ recipients, confirming the role of P2X7R in allograft rejection (Figure 5A). The ability of oATP to prolong cardiac transplant survival was severely altered in $P2X7R^{-/-}$ mice, suggesting that in the context of cardiac alloimmune response, oATP acts mainly, although not exclusively, through P2X7R (Figure 5A). Moreover, these data suggest that compensatory mechanisms exist in $P2X7R^{-/-}$ mice; indeed, ATP has been shown to signal

through other P2XsR, particularly through P2X1R and P2X4R in the context of T cell activation and immune function[21]. We thus analyzed $CD4^+$ T cells obtained from $P2X7R^{-/-}$ mice by western blot, and an upregulation of P2X1R and P2X4R was observed compared to wild-type mice (Figures 5B, 5C and 5D). Given these data, we hypothesize that the upregulation of P2X1R and P2X4R may partially compensate for P2X7R function in our model. Moreover, analysis of T cell populations in $P2X7R^{-/-}$ mice revealed higher percentages of Teff and Treg cells (Figures 5E and 5F, respectively), thus demonstrating that genetic deletion of P2X7R and the compensatory upregulation of other P2XsR exert profound and complex effects on T cell activation and homeostasis.

In vitro P2X7R targeting inhibits $CD4^+$ T cell activation and Th1/Th17 differentiation

To address the mechanisms underlying P2X7R targeting-mediated inhibition of cardiac transplant rejection, we analyzed the effect of P2X7R targeting on T cell activation and Th1/Th17 differentiation *in vitro*. P2X7R was expressed on $CD4^+$ and $CD8^+$ T cells isolated from splenocytes, as assessed by western blotting and rt-PCR, with higher expression levels observed in $CD4^+$ T cells (Figures 6A and 6B). We then tested the effect of *in vitro* P2X7R targeting with oATP during $CD4^+$ T cell activation. Firstly, in an ELISPOT assay, naïve $CD4^+$ T cells were stimulated with 0.5 μg/ml anti-CD3-Ig and anti-CD28-Ig for 24 hours, and when 100 μM oATP was added to cultures, the number of IFN-γ-producing $CD4^+$ T cells was significantly reduced compared to controls (Figure 6C). Secondly, in a T cell proliferation assay, CFSE-labeled naïve $CD4^+$ T cells were stimulated for 96 hours with 0.5 μg/ml anti-CD3-Ig and anti-CD28-Ig, and treatment with 100 μM oATP diminished $CD4^+$ T cell proliferation (Figure 6D, lower panel) compared to controls (Figure 6D, upper panel). Expression levels of the P2XsR were not influenced by the presence of oATP during anti-CD3-Ig/anti-CD28-Ig stimulation (Figure S1A). To assess whether oATP is specific for P2X7R or whether it also induces its effect through the inhibition of other purinergic receptors (e.g. P2X1R or P2X4R, which have been involved in immune function[21]), we combined 100μM oATP with 50μM P2X1R (NF-449) and 50μM P2X4R (5-BDBD) inhibitors; a further suppression of anti-CD3-Ig/anti-CD28-Ig-mediated IFN-γ production was obtained (Figure 6E). These data demonstrate that the concentration of oATP is not (at least not completely) blocking P2X1R and P2X4R. We next tested the effect of *in vitro* P2X7R targeting during a Th1/Th17 generation and differentiation assay. A small percentage of naïve Th0 $CD4^+$ T cells ($CD4^+CD25^-$) were shown to express P2X7R (Figures 6F and 6G); however, when Th0 $CD4^+$ T cells were activated and differentiated in the appropriate cytokine milieu into Th1 or Th17 cells, an upregulation of P2X7R was observed (Figures 6F, 6H and 6I). P2X7R targeting with oATP inhibited Th0 conversion into both Th1 (Figures 6J and 6K) and Th17 (Figures 6L and 6M), as assessed by the percentage of IFN-γ^+ and IL-17^+ cells, respectively. We show, therefore, that P2X7R targeting through oATP suppresses activation, proliferation and Th1/Th17 differentiation of $CD4^+$ T cells. We then further investigated the role of P2X7R on T cell activation and Th1/Th17 differentiation by genetic upregulation of P2X7R. P2X7R cDNA was transduced using a pMY-IRES-GFP retroviral vector into $CD4^+$ T cells (pmY-P2X7R $CD4^+$ T cells), and upregulation of P2X7R expression was confirmed by western blot (Figure S2A). pmY-P2X7R $CD4^+$ T cells were then challenged with anti-CD3-Ig/anti-CD28-Ig stimulation in an ELISPOT assay. A greater number of IFN-γ-producing cells was observed in pmY-P2X7R $CD4^+$ T cells compared to cells transduced with the empty vector (pmY-mock $CD4^+$ T cells) (Figure S2B). In a Th1/Th17 generation assay, pmY-P2X7R $CD4^+$ T cells seemed to display increased differentiation capacity compared to pmY-mock $CD4^+$ T cells, as assessed by T-bet (Figures S2C and S2D) and ROR-γ expression (Figures S2E and S2F).

In vitro and *in vivo* P2X7R targeting inhibits STAT3 phosphorylation

We next assessed which molecular pathway during T cell activation was preferentially inhibited by the targeting of P2X7R. Several key components of T cell receptor signaling involved in the alloimmune response [34] were examined, and the phosphorylation kinetics following *in vitro* anti-CD3-Ig/anti-CD28-Ig-mediated $CD4^+$ T cell activation was evaluated using the Luminex assay[35]. Peak phosphorylation for the analyzed pathways was observed at 30 minutes for JNK/SAPK1 and at 60 minutes for p70/S6, STAT3 and STAT5; a second peak was seen for STAT5at 24 hours (Figure 7A). A significant inhibition of activation-induced STAT3 phosphorylation was observed when oATP was added to the culture (Figure 7E), while the phosphorylation of JNK/SAPK1, p70/S6 or STAT5 in $CD4^+$ T cells was unaffected (Figures 7B, 7C and 7D, respectively). We then confirmed by western blot that oATP dose-dependently inhibits STAT3 phosphorylation (Figure 7F). To demonstrate that the effect of oATP is STAT3-phosphorylation-inhibition-dependent, we tested the effect of Colivelin treatment, a peptide that promotes STAT3 phosphorylation[36, 37] in an add-back experiment. We first confirmed that Colivelin (Col) was able to restore the activation-induced phosphorylation of STAT3 in a dose-dependent manner in oATP-treated $CD4^+$ T cells by western blotting (Figure 7G). Moreover, in an ELISPOT assay, in which naïve $CD4^+$ T cells were stimulated with 0.5 μg/ml anti-CD3-Ig and anti-CD28-Ig, treatment with Colivelin was shown to significantly revert oATP-mediated suppression of IFN-γproducing cells (Figure 7H). The effect of oATP and Colivelin on STAT3 phosphorylation and T cell function was also evaluated following cardiac transplantation. BALB/c hearts were transplanted into C57BL/6 mice, and STAT3 phosphorylation was assessed by western blot in $CD4^+$ T cells isolated from splenocytes of mice 7 days after transplantation. oATP-treated mice displayed reduced levels of phosphorylated STAT3 compared to untreated mice, and paralleling the results obtained *in vitro*, the use of Colivelin was able to reestablish STAT3 phosphorylation in $CD4^+$ T cells of oATP-treated mice (Figures 7I and 7J). From a functional point of view, the use of Colivelin greatly abrogated the effect of oATP on allograft survival (Figure 7K). These data demonstrate that P2X7R signaling is crucial for T cell activation and Th1/Th17 generation and that this effect is STAT3-dependent.

In vivo short-term P2X7R targeting prevents coronary vasculopathy in a model of chronic heart cardiac transplant rejection

In order to evaluate the importance of P2X7R signaling and targeting in a clinically relevant setting, we tested the effect of oATP treatment in a model of cardiac transplant chronic rejection (bm12 donors to C57BL/6 recipients). In this model, C57BL/6 mice do not acutely reject bm12 cardiac allografts, but transplanted hearts develop transplant-associated coronary vasculopathy. Cardiac allograft pathology was assessed 40 days after transplantation of bm12 hearts into C57BL/6 mice. Advanced coronary vasculopathy and severe lymphocyte and macrophage interstitial and vascular infiltration was observed in untreated mice (Figures 8A1–8A4) as compared to oATP-treated mice (Figures 8B1–8B4), which displayed only mild cellular infiltration as well as absence of coronaropathy (Figures 8C and 8D, respectively). oATP-treated mice also showed a reduced number of IFN-γ-producing cells (Figure 8E) and an increased number of IL-4-producing cells (Figure 8F) in an ELISPOT assay when splenocytes were challenged with donor antigens.

DISCUSSION

The introduction of novel immunosuppressive drugs has led to significant improvement in short-term cardiac transplant survival rates but has been unable to significantly improve allograft survival in the long-term[1, 2] Furthermore, current immunosuppressive regimens are associated with multiple complications including cancer, opportunistic infections, diabetes, kidney failure, and hypertension[2–4]. In order to improve transplantation outcomes, it is

therefore critical to continue development of novel strategies in order to lessen the need for life-long immunosuppression and to achieve stable graft acceptance. We thus studied the role of the ionotropic purinergic P2X receptors (a family of receptors with largely unknown function in the alloimmune response) in cardiac transplant rejection and tolerance.

Aside from signal 1 (TCR engagement) and signal 2 (costimulatory molecule interaction), soluble signals have also been recognized as major players in T cell activation; we predicted that ATP would exert a fundamental role in the context of allograft organ rejection, in particular in the first phase after transplantation when it could be released in marked amounts by necrotic or ischemic cells. Among all P2XsR, our data show that P2X7R is specifically upregulated during the alloantigen response in the graft and is expressed by virtually all T cells infiltrating the graft. On the contrary, P2X1R and P2X4R are similarly increased in both syngrafts and allografts, and their upregulation may thus be more related to ischemia reperfusion injury and to post transplant inflammation than specifically to the alloantigen response. Notably, we found P2X7R to be upregulated in T cells infiltrating cardiac transplants during clinical acute rejection, confirming the relevance of the P2X7R pathway in patients undergoing heart transplantation. *In vivo*, short-term P2X7R targeting with oATP robustly promoted long-term cardiac transplant survival in 80% of the recipients in a fully mismatched model of heart transplantation; moreover, oATP was able to inhibit the development of coronary vasculopathy in a chronic model of cardiac rejection. oATP was initially and primarily described as a P2X7R inhibitor[28] and, although recent papers have pointed to a broader effect of oATP as an inhibitor of other purinergic receptors[20], oATP remains to date the most well-characterized and effective drug to target *in vivo* P2X7R[38, 39]. The relative ineffectiveness of oATP treatment in P2X7R$^{-/-}$ mice appears to confirm that, although additional inhibition of other purinergic receptor may be present, there is a more restricted P2X7R-mediated effect in our model; moreover, our *in vitro* data show that at the concentration used, oATP does not (at least not completely) inhibit other P2XsR. P2X7R targeting is associated with a reduction in Teff and Th17 cells, which are known to be highly relevant to the alloimmune response, and we observed a reduction in the Th1/Th17 lympocytic infiltrate. Inhibition of the anti-graft effector T cell compartment (Th1 and Th17) may thus be responsible for the observed long-term graft function. Although P2X7R inhibition has been related to a Th17-to-Treg shift in *in vitro* assays[23] and in a model of inflammatory bowel disease[14], flow cytometric analysis of treated mice does not support a clear expansion of the Treg compartment (observed only later after treatment) in our model. In contrast, our adoptive transfer experiments show an inhibition of the anti-graft effector T cell compartment as well as demonstrate a state of anergy toward graft antigens in treated mice, which is likely responsible for the observed long-term graft survival. Anergy toward alloantigens does not seem to be related to a state of chronic immunosuppression, as demonstrated by the preserved anti-Ovalbumin response after immunization, which is particularly applicable to the clinical setting. From a molecular point of view, targeting P2X7R appears to be a result of activation-mediated STAT3 phosphorylation, given the reduced level of phosphorylated STAT3 following oATP treatment. Furthermore, Colivelin treatment, which restores STAT3 phosphorylation, reverts, although not completely, the effect of *in vitro* and *in vivo* oATP treatment, showing that other pathways may be affected by oATP[14, 18]. STAT3 is a well-known transcription factor with multiple roles in mediating T cell activation and proliferation[22, 40, 41]. Our *in vitro* and *in vivo* data point to a novel axis in T cell activation, which links ATP-P2X7R-STAT3 and activation of the anti-graft effector T cell compartment (Th1 and Th17 cells), which can be inhibited by the use of oATP. The centrality of this pathway at the crossroads of T cell activation and differentiation is further demonstrated by the transduction of P2X7R on T cells and the associated effects of greater activation and Th1/Th17 differentiation. The P2X7R pathway in T cells is highly important in the context of cardiac transplant rejection and may synergize with the P2X7R pathway in APCs[18] to promote graft rejection. Willhem and colleagues have recently described a role

for P2X7R in graft-versus-host disease[18] using the P2X7R$^{-/-}$ model; in comparison, (i) we tested a pharmacological inhibitor of P2X7R, which is more clinically relevant; (ii) we tested the effect of P2X7R targeting in 2 different models of solid organ transplantation (i.e. the acute and the chronic rejection model); (iii) we demonstrated a direct effect of P2X7R inhibition on T cells, which is independent of the inhibitory effect on APC function; (iv) we showed that the effect of P2X7R targeting is mediated by an inhibition of the T cell effector compartment more than by an expansion of the regulatory T cell compartment; (v) we highlight the necessity of exercising some caution in the analysis of data using P2X7R$^{-/-}$ mice given that the upregulation of other P2XsR (in the knock-out mouse, but not during pharmacological targeting) may partially obscure P2X7R function. On the NIH clinical trials website (http://clinicaltrials.gov), nearly 80 clinical trials are registered to promote tolerance in transplantation. None of these trials is specifically aimed or designed to target P2X7R-mediated alloimmunity, yet our results clearly indicate the need for novel therapeutic options for transplantation. We envision P2X7R-mediated immunity as a novel pathway for cardiac transplant rejection. Indeed, a P2XR targeting strategy has considerable translational potential, as novel anti-P2X7R inhibitors are available for clinical use (e.g. oATP, CE 224,535, AZD9056 and GSK1482160). Short-term P2X7R-targeting at the time of transplantation may prove to be valuable in the clinical setting by promoting cardiac transplant acceptance, lessening the need for chronic immunosuppression and preventing the development of coronary graft vasculopathy.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Clinical Summary

Heart transplantation is a lifesaving procedure for patients with end-stage heart failure and provides a better survival and quality of life as compared to medical treatment or device-based therapies. Recently, advances in immunosuppression and improved clinical care, have enhanced the early survival of transplanted patients. However, more then 20% of patients do not survive beyond 3 years, and those who survive are afflicted with the long-term complications associated with chronic immunosuppression (e.g. post-transplant diabetes mellitus, coronary vasculopathy, nephropathy, infections, and malignancies). In order to improve transplantation outcomes and lessen the need for life-long immunosuppression, it is crucial to continue the development of novel immunomodulatory strategies. Short-term targeting of the purinergic receptor P2X7R may provide a novel therapeutic opportunity. Soon after transplantation, purine adenosine 5′-triphosphate (ATP) is released by necrotic cells and causes the activation of graft-infiltrating Tcells, which sense ATP by the highly-expressed receptor P2X7R. Our data show that short-term P2X7R targeting with periodate-oxidized-ATP (oATP) robustly promotes, in a fully-mismatched model of acute rejection, long-term cardiac transplant survival in 80% of recipients, with preservation of immunocompetence. Moreover, oATP inhibits the development of coronary vasculopathy in a model of chronic rejection. Nearly 80 clinical trials are registered on the NIH website to promote long-term graft function, and none of these is designed to target P2X7R-mediated alloimmunity. As novel P2X7R inhibitors are available for clinical use (e.g. oATP, CE-224,535, AZD9056 and GSK1482160), short-term P2X7R-targeting may have considerable translational potential by promoting cardiac transplant acceptance, thereby lessening the need for chronic immunosuppression and preventing the development of coronary vasculopathy.

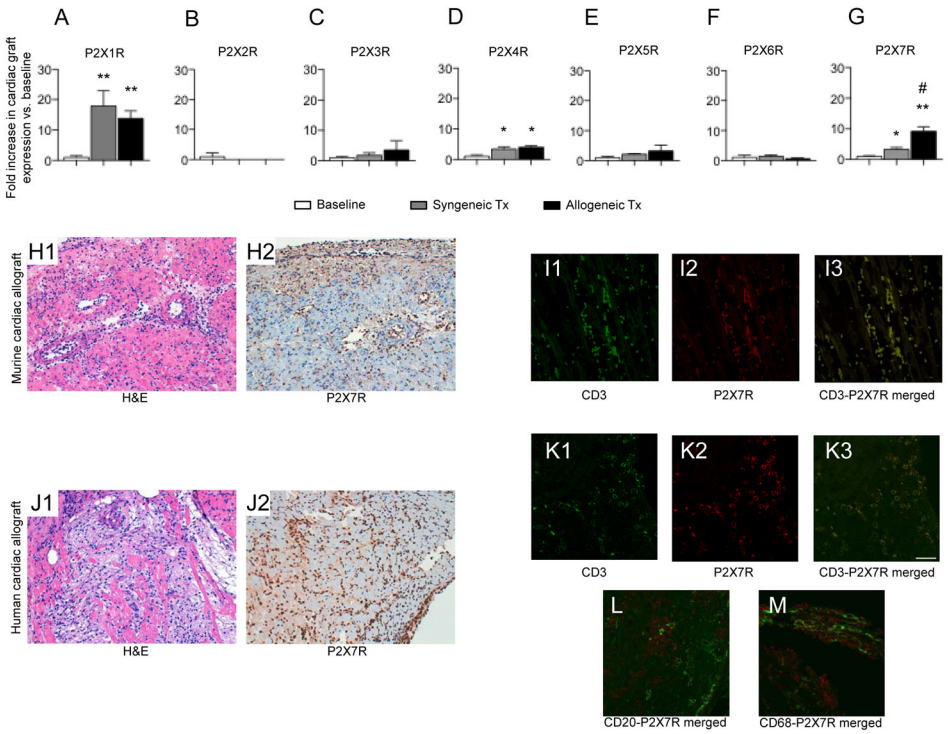

Figure 1.

Syngeneic C57BL/6 (Syngeneic Tx) and allogeneic BALB/c cardiac transplants (Allogeneic Tx) were harvested from C57BL/6 recipient mice 7 days post-transplantation, and P2XsR mRNA levels were compared to untransplanted BALB/c hearts (Baseline). An upregulation of P2X1R (A), P2X4R (D), and P2X7R (G) expression in both syngrafts and allografts was evident compared to baseline (n=3, *$p<0.05$, **$p<0.01$); greater P2X7R upregulation was observed in allogeneic compared to syngeneic heart transplants (n=3, #$p<0.05$; G). No upregulation for P2X2R (B), P2X3R (C), P2X5R (E) and P2X6R (F) was observed. Substantial infiltration was observed at day 7 after transplantation in allografts (H1). Immunohistochemistry revealed that mononuclear infiltrating cells were positive for P2X7R expression (H2), while myocytes, endothelial cells and fibroblast showed no expression (H2). Immunofluorescence confirmed complete overlapping between $CD3^+$ T cells and P2X7R expression (I1, I2, I3). P2X7 was expressed in lymphocytes infiltrating human cardiac transplants undergoing acute rejection as well (J1–J2). Complete overlapping between $CD3^+$ T cells and P2X7R was also demonstrated (K1, K2, K3) while no colocalization was observed between P2X7R (red; L, M) and $CD20^+$ B cells (green, L) or $CD68^+$ macrophages (green, M).

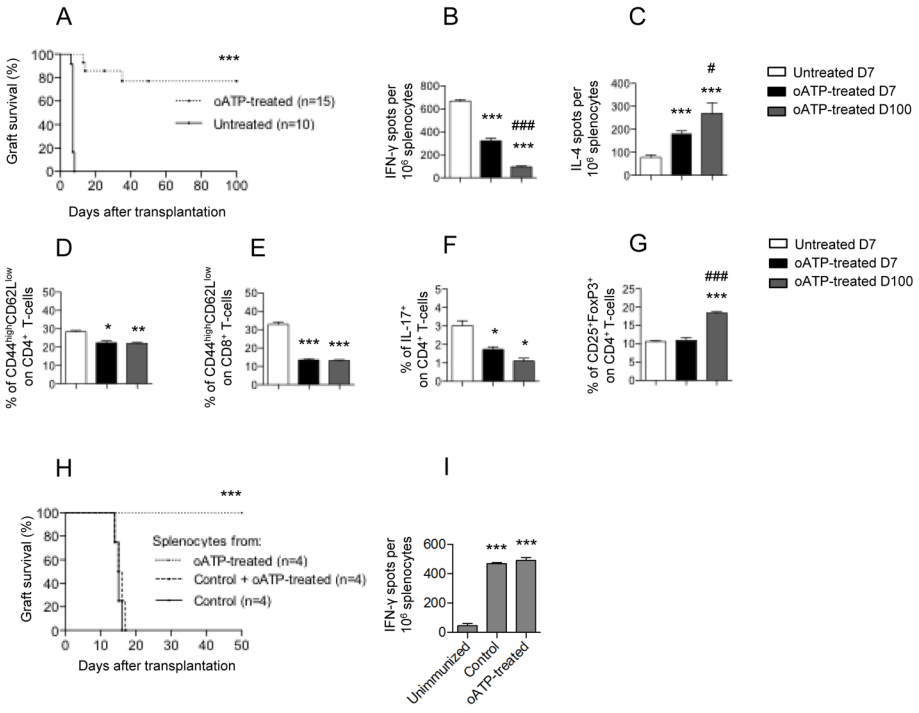

Figure 2.

P2X7R inhibition with oATP in the BALB/c into C57BL/6 cardiac transplantation model prevented transplant rejection in 80% of transplants (n=15, ***p<0.001 vs. Untreated; A). When recipient splenocytes were re-challenged with donor splenocytes in an ELISPOT assay at day 7 after transplantation, they displayed fewer IFN-γ-producing cells (n=5, ***p<0.001 vs. Untreated day 7; B) and more IL-4-producing cells (n=5, ***p<0.001 vs. Untreated day 7; C) with further polarization at day 100 (n=5, IFN-γ: ###p<0.001; IL-4: #p<0.05 vs. Untreated and oATP-treated day 7; B, C). A significant reduction in the number of $CD4^+$ Teffs (n=5, *p<0.05, **p<0.01 vs. Untreated day 7; D), $CD8^+$ Teffs (n=5, ***p<0.001 vs. Untreated day 7; E), and IL-17^+CD4^+ T cells (n=5, *p<0.05 vs. Untreated day 7; F) was observed at days 7 and 100 in oATP-treated mice. No differences in the percentages of peripheral Tregs were observed between oATP-treated and untreated mice at day 7, while an increase in the Treg population was seen at day 100 (n=5, ***p<0.001 vs. Untreated day 7, ###p<0.001 vs. oATP-treated day 7; G). BALB/c cardiac transplant rejection was observed in C57BL/6 $Rag^{-/-}$ mice adoptively transferred with naïve C57BL/6 splenocytes alone (Controls) or in combination with splenocytes from oATP-treated mice, while prolonged graft survival was observed when splenocytes from oATP-treated mice were transferred alone (n=4, ***p<0.001 vs. Controls; H). Immunocompetence was preserved in oATP-treated mice as assessed by *in vitro* Ovalbumin response after *in vivo* immunization (n=3, ***p<0.001 vs. Unimmunized; I).

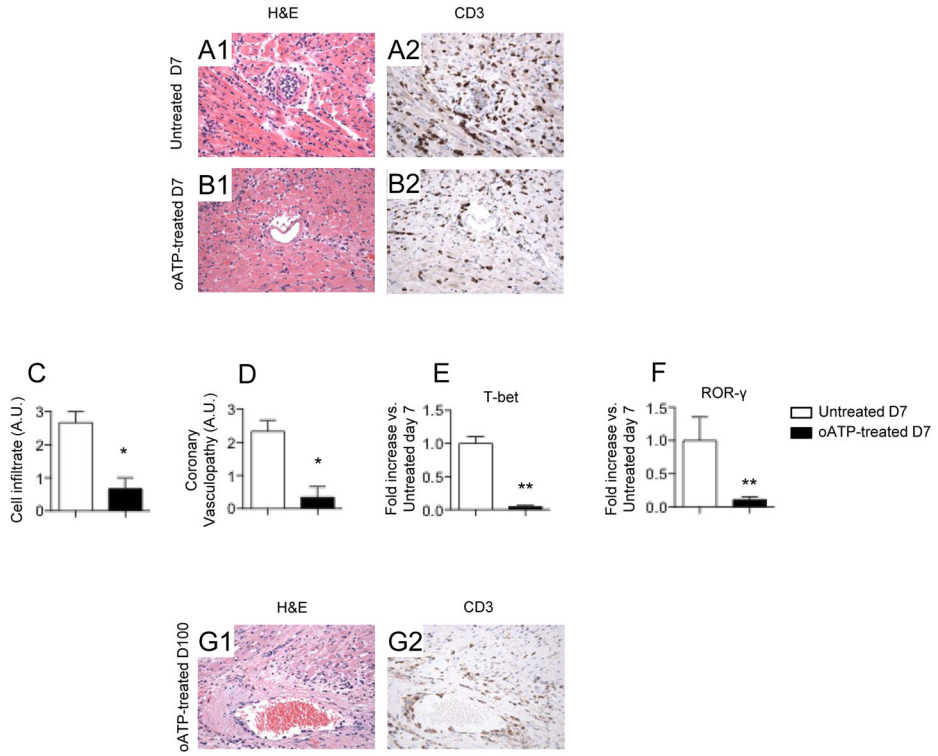

Figure 3.

Histological analysis of cardiac transplants at day 7 after transplantation revealed preserved graft parenchyma, reduced artery lumen occlusion, and fewer numbers of $CD3^+$ graft-infiltrating cells in oATP-treated (B1, B2) compared to untreated mice (A1, A2). Semi-quantification of graft-infiltrate (n=5, *p<0.05 vs. Untreated day 7; C) and coronary vasculopathy (n=5, *p<0.05 vs. Untreated day 7; D) confirmed the protection conferred by oATP treatment. T-bet (a Th1 marker) (n=3, **p<0.01 vs. Untreated day 7; E) and ROR-γ (a Th17 marker) (n=3, **p<0.01, vs. Untreated day 7; F) transcripts were reduced in oATP-treated compared to untreated mice. Preserved parenchyma, mild coronary vasculopathy and very few $CD3^+$ lymphocytes and $MAC2^+$ macrophages were observed at 100 days after transplantation in oATP-treated mice with long-term functioning cardiac transplants (G1, G2).

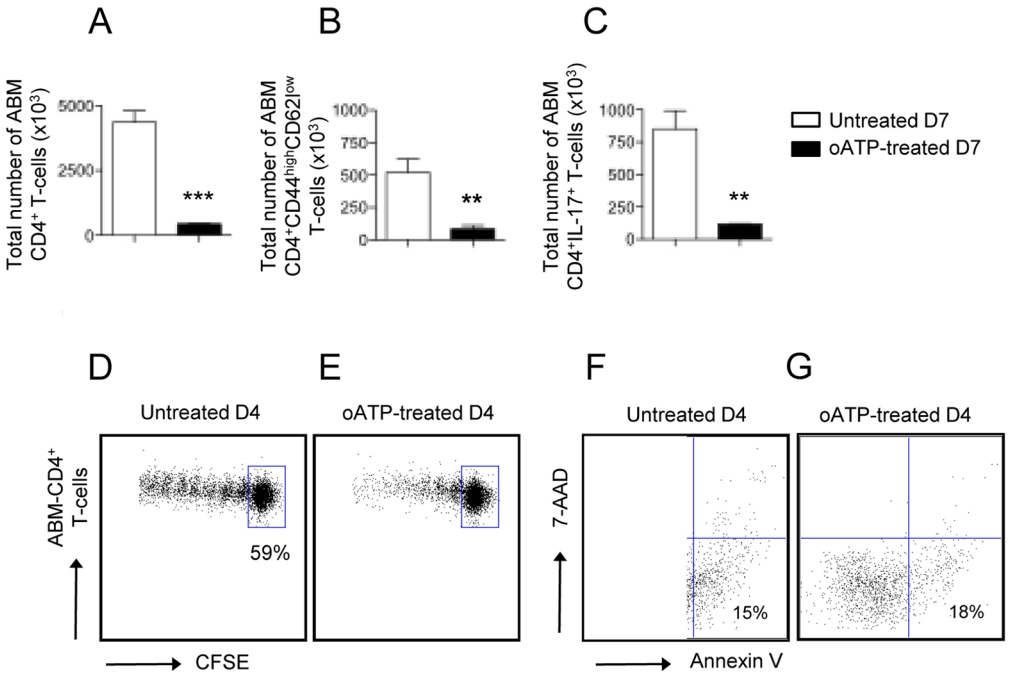

Figure 4.

ABM TCR-Tg $CD4^+$ T cells were injected i.p. into bm12 cardiac-transplanted C57BL/6 $Rag^{-/-}$ mice. Reduced numbers of ABM TCR-Tg $CD4^+$ T cells were observed after 7 days in the spleens of oATP-treated compared to untreated mice (n=3, ***p<0.001 vs. Untreated day 7; A). A significant reduction in the numbers of $CD4^+$ Teffs (n=3, **p<0.01 vs. Untreated day 7; B) and Th17 cells (n=3, **p<0.01 vs. Untreated day 7; C) was also evident. ABM TCR-Tg $CD4^+$ T cells were then labeled with the intracellular dye CFSE before injection and were harvested after 4 days; significant inhibition of proliferation was observed in oATP-treated mice (E) compared to untreated mice (D). Data are representative of 3 experiments. Similar levels of apoptosis (% of $AnnexinV^+7AAD^-$cells) of ABM TCR-Tg $CD4^+$ T cells were observed in untreated and oATP-treated mice (F and G, respectively, representative of 3 experiments).

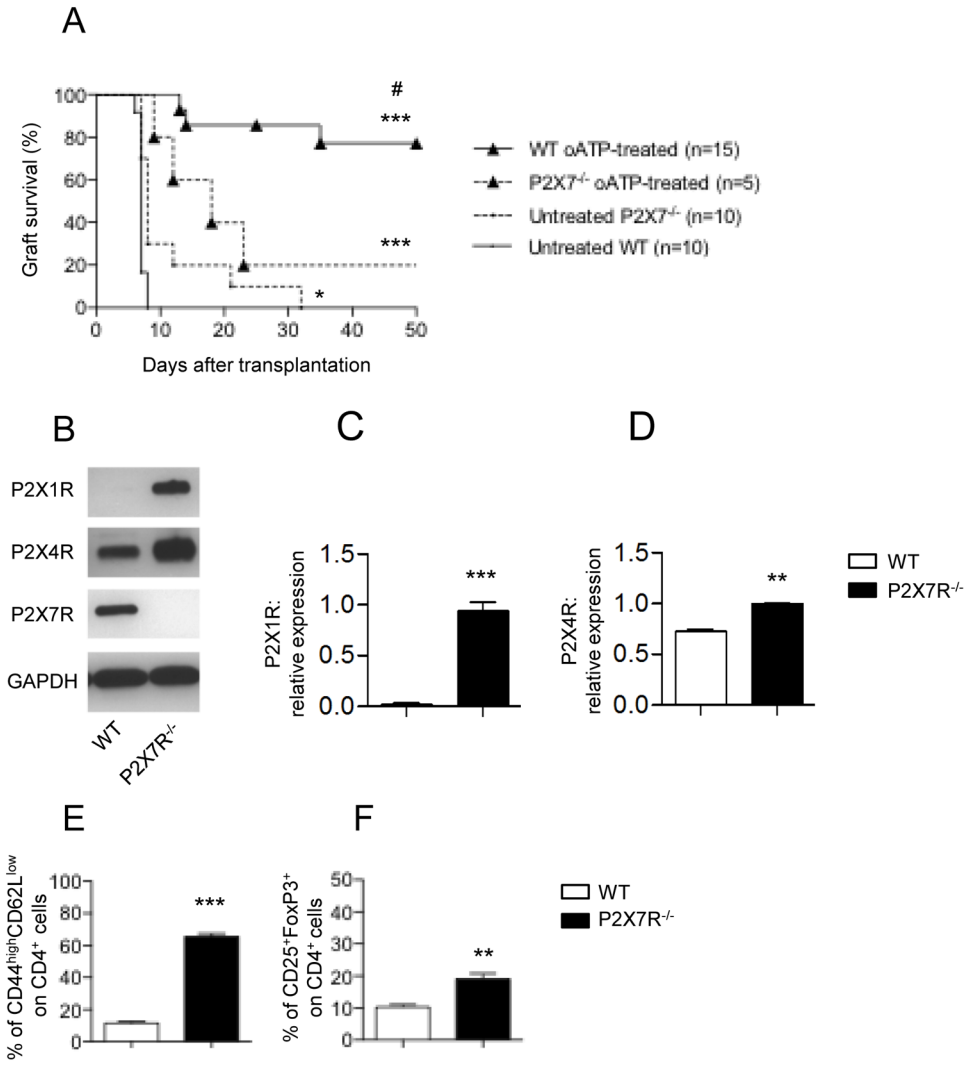

Figure 5.

BALB/c hearts were transplanted into WT or P2X7R$^{-/-}$ C57BL/6 mice; graft survival prolongation was observed in P2X7R$^{-/-}$ recipients (*p<0.05 vs. WT untreated; A); oATP treatment was less effective in prolonging cardiac transplant survival in P2X7R$^{-/-}$ mice compared to WT (***p<0.001 vs. WT Untreated; #p<0.05 vs. all; A). Western blot analysis of CD4^{+} T cells revealed higher P2X1R and P2X4R expression in P2X7R$^{-/-}$ compared to WT mice (n=3, **p<0.01; ***p<0.001 vs. WT; B, C, D). Greater numbers of CD4^{+} T effector (n=3; ***p<0.001 vs. WT; E) and T regulatory cells (n=3; **p<0.01 vs. WT; F) were present in P2X7R$^{-/-}$ compared to WT mice.

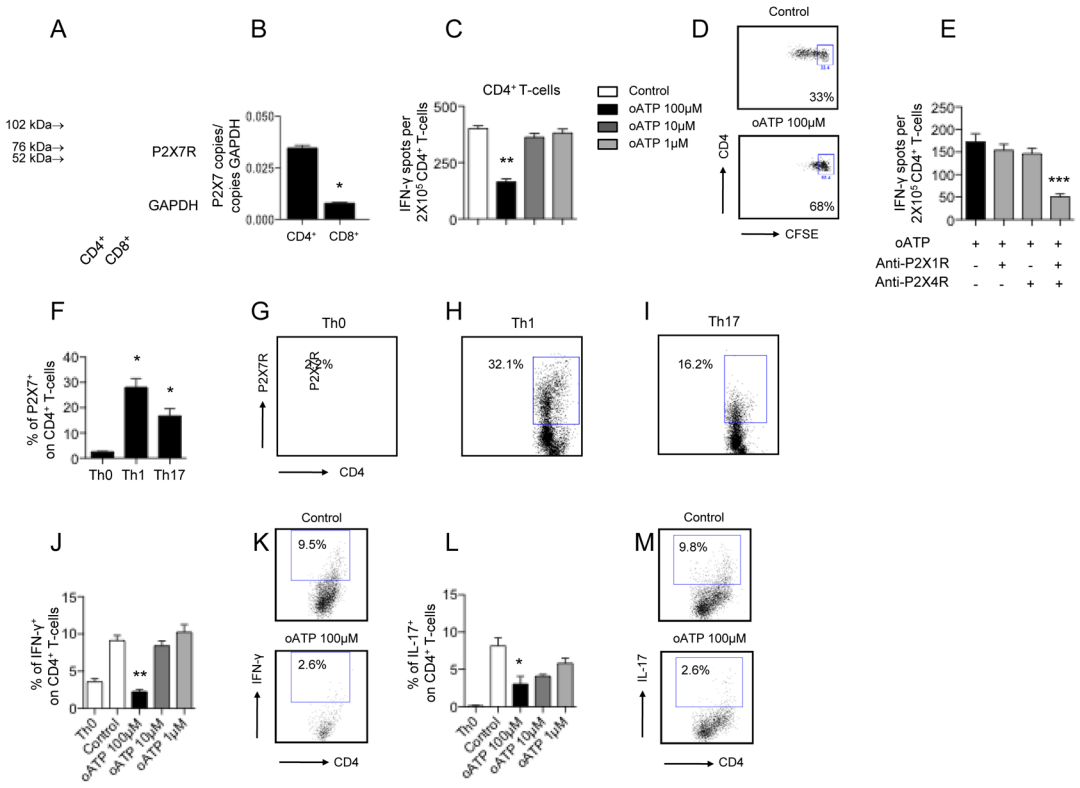

Figure 6.

Greater P2X7R expression was observed in $CD4^+$ compared to $CD8^+$ T cells, as assessed by western blot (A) and rt-PCR analysis (B) (n=3, *p<0.05 vs. $CD4^+$ T cells). Anti-CD3-Ig/ anti-CD28-Ig-stimulated $CD4^+$ T cells were used in an ELISPOT assay in conjunction with oATP treatment, and a reduction in IFN-γ-producing $CD4^+$ T cells was observed (n=5, **p<0.01 vs. Control; C). CFSE dilution analysis revealed a lesser number of proliferating $CD4^+$ T cells (D, lower panel; representative of 3 different experiments) in the presence of oATP compared to control (D, upper panel; representative of 3 different experiments). In an ELISPOT assay, IFN-γ production in $CD4^+$ T cells was further inhibited when anti-P2X1R and anti-P2X4R were added (n=5, ***p<0.001 vs. oATP; E). While naïve Th0 cells displayed marginal P2X7R expression, when they were differentiated into Th1 or Th17 cells, an upregulation of P2X7R in these cells was observed (n=3, *p<0.05 vs. naïve Th0; F, G, H, I). In our Th1/Th17 differentiation assay, reduced numbers of IFN-γ^+ (n=4, **p<0.01 vs. Control [no oATP]; J, K) and IL-17^+ (n=4, *p<0.05 vs. Control; L, M) $CD4^+$ T cells were generated in the presence of oATP.

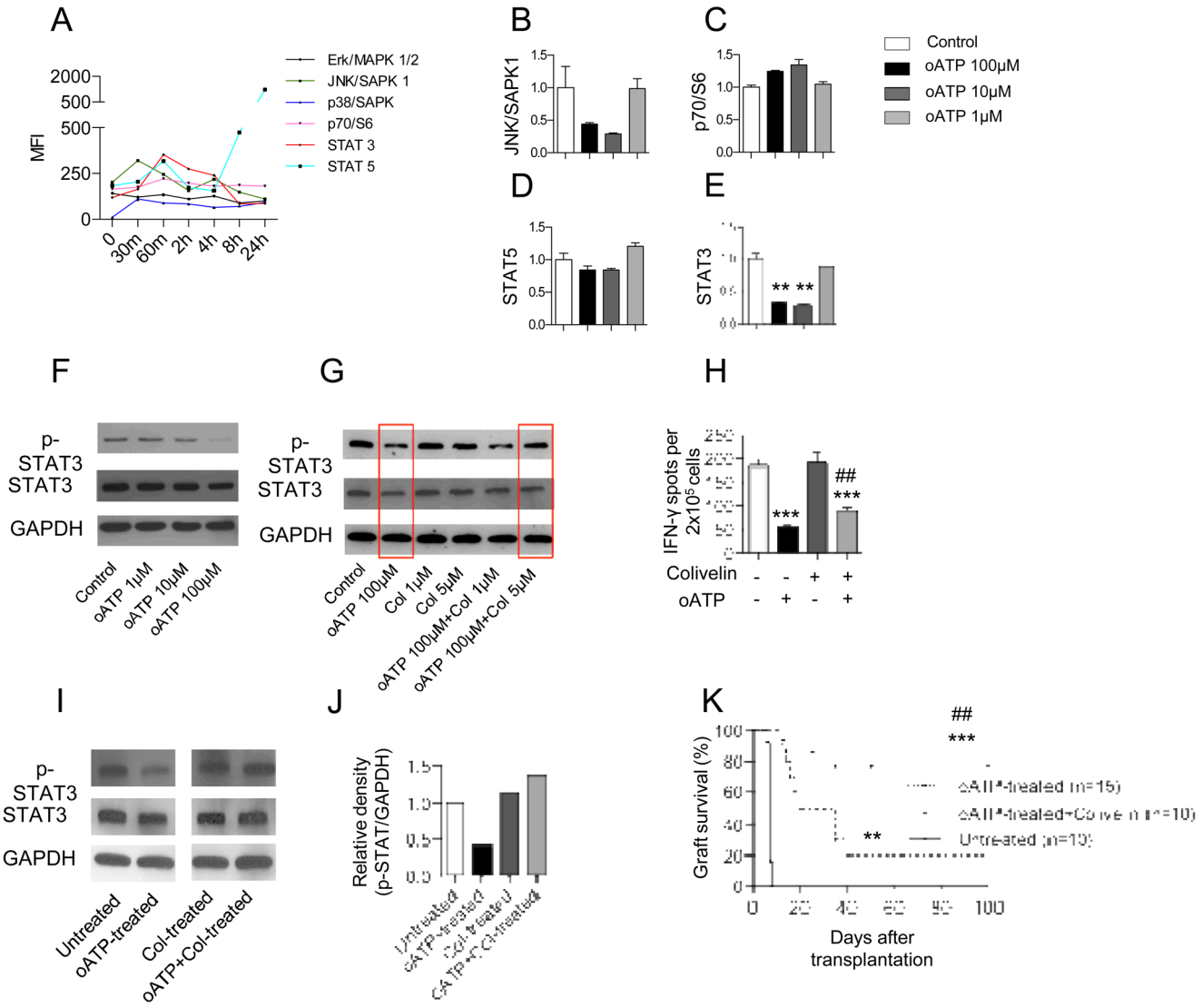

Figure 7.

Peak phosphorylation (assayed by Luminex) of JNK/SAPK1 was evident at 30 minutes following anti-CD3-Ig and anti-CD28-Ig stimulation in $CD4^+$ T cells, while peaks in p70/S6, STAT3, and STAT5 phosphorylation were evident at 60 minutes; a second peak of phosphorylation for STAT5 was evident at 24 hours (A) (shown as MFI [mean fluorescence intensity]). P2X7R targeting via oATP treatment inhibited activation-induced STAT3 phosphorylation (n=3, **p<0.01 vs. Control, E), while target of P2X7R had no effect on phosphorylation of JNK/SAPK1 (B), p70/S6 (C), or STAT5 (D). Western blot analysis confirmed reduced STAT3 phosphorylation dose dependently with oATP treatment (F; representative of 3 different experiments). 0.1 μM Colivelin (Col) prevented oATP-mediated inhibition of STAT3 phosphorylation (G) and rescued $CD4^+$ T cells from oATP-mediated suppression of IFN-γ production (n=8, ***p<0.001 vs. Colivelin[−]/oATP[−]; ##p<0.01 vs. Colivelin[−]/oATP[+]; H). In our allogeneic model of cardiac transplantation, oATP treatment inhibited STAT3 phosphorylation in $CD4^+$ T cells (I, J). Colivelin restored STAT3 phosphorylation on $CD4^+$ T cells (I, J) and significantly impaired the prolongation of cardiac transplant survival associated with oATP treatment (K; **p<0.01 and ***p<0.001 vs. Untreated; ##p<0.01 vs. oATP+Colivelin).

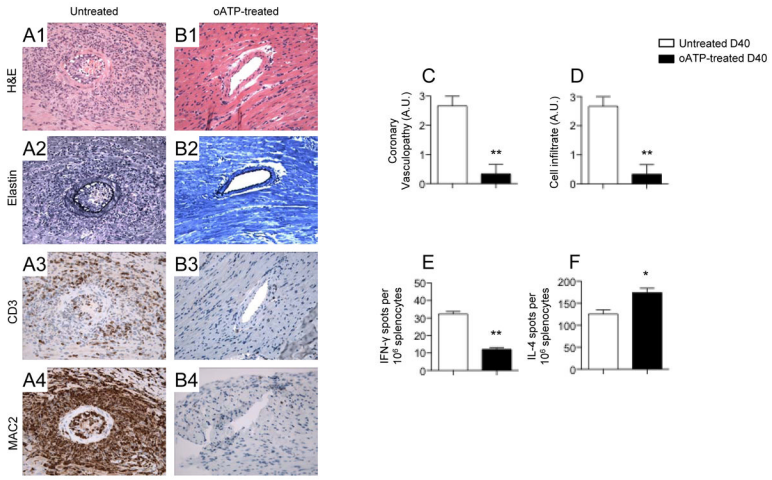

Figure 8.

Bm12 hearts were transplanted in C57BL/6 recipients, and histological analysis of the transplants was performed at day 40 after transplantation. H&E and elastin staining showed advanced intimal proliferation and vascular occlusion of the arteries in untreated mice (A1, A2), while preserved vessel morphology was observed in oATP-treated mice (B1, B2). Massive vascular and parenchymal T cell (A3) and macrophage (A4) infiltration was seen in untreated mice, but not in oATP-treated mice (B3, B4). Semi-quantification of coronary vasculopathy (C) and infiltration (D) confirmed that cardiac transplants were protected by oATP treatment (n=3; **p<0.01 vs. Untreated day 40). Results of an ELISPOT assay showed reduced numbers of IFN-γ-producing cells (E) and increased numbers of IL-4-producing cells (F) among recipient splenocytes challenged with donor antigens in oATP-treated mice (n=3; *p<0.05; **p<0.01 vs. Untreated day 40).

Table 1

Patient characteristics (Data are expressed as Mean±SD)

Year of transplantation:	2011
Number of transplantation:	23
Sex (M/F):	16/7
Age (years):	47±15
End-stage heart failure etiology:	
-Post-ischemic	6 (26.9%)
-Dilated CMP	11 (47.8%)
-Valvular CMP	2 (8.7%)
-Retransplantation	1 (4.3%)
-Hypertrophic CMP	1 (4.3%)
-Post-correction congenital CMP	1 (4.3%)
-CMP associated with Steinert	1 (4.3%)
myotonic dystrophy syndrome	
Initial immunosuppressive regimen*:	
-Induction	ATG
-Maintenance	Csa+Methylprednisolone +Mycofenolate Mofetil
Acute graft rejection episodes**:	10 (43.8%)
Mortality:	
*-Acute rejection 3R,(50 days after transplantation)****	1 (4.3%)
-Multi Organ Failure (70 days after	1 (4.3%)
transplantation)	
Donor:	
-Age (years)	45±13
-Ischemia (minutes)	185±53

Abbreviations: CMP (Cardiomiopathy); ATG (Thymoglobulin); Csa (Cyclosporine).

*Immunosuppressive regimen was subsequently tuned according to patient conditions[30];

**Requiring intravenous steroids treatment;

***Assessed for P2X7R expression.