Targeting the adenosine 2A receptor enhances chimeric antigen receptor T cell efficacy

Paul A. Beavis,1,2 Melissa A. Henderson,1,2 Lauren Giuffrida,1,2 Jane K. Mills,1,2 Kevin Sek,1,2 Ryan S. Cross,1,2 Alexander J. Davenport,1,2 Liza B. John,1,2 Sherly Mardiana,1,2 Clare Y. Slaney,1,2 Ricky W. Johnstone,1,2 Joseph A. Trapani,1,2 John Stagg,3,4 Sherene Loi,1,2 Lev Kats,1,2 David Gyorki,5 Michael H. Kershaw,1,2,6,7 and Phillip K. Darcy1,2,6,7

1Cancer Immunology Program, Peter MacCallum Cancer Centre, East Melbourne, Victoria, Australia. 2Sir Peter MacCallum Department of Oncology, University of Melbourne, Parkville, Victoria, Australia. 3Centre de Recherche du Centre Hospitalier de l’Université de Montréal, Institut du Cancer de Montréal, Montréal, Quebec, Canada. 4Faculté de Pharmacie, Université de Montréal, Pavillon Jean-Coutu, Montréal, Quebec, Canada. 5Division of Cancer Surgery, Peter MacCallum Cancer Centre. 6Department of Immunology, Monash University, Clayton, Victoria, Australia. 7Department of Pathology, University of Melbourne, Parkville, Victoria, Australia.

Chimeric antigen receptor (CAR) T cells have been highly successful in treating hematological malignancies, including acute and chronic lymphoblastic leukemia. However, treatment of solid tumors using CAR T cells has been largely unsuccessful to date, partly because of tumor-induced immunosuppressive mechanisms, including adenosine production. Previous studies have shown that adenosine generated by tumor cells potently inhibits endogenous antitumor T cell responses through activation of adenosine 2A receptors (A2ARs). Herein, we have observed that CAR activation resulted in increased A2AR expression and suppression of both murine and human CAR T cells. This was reversible using either A2AR antagonists or genetic targeting of A2AR using shRNA. In 2 syngeneic HER2+ self-antigen tumor models, we found that either genetic or pharmacological targeting of the A2AR profoundly increased CAR T cell efficacy, particularly when combined with PD-1 blockade. Mechanistically, this was associated with increased cytokine production of CD8+ CAR T cells and increased activation of both CD8+ and CD4+ CAR T cells. Given the known clinical relevance of the CD73/adenosine pathway in several solid tumor types, and the initiation of phase I trials for A2AR antagonists in oncology, this approach has high translational potential to enhance CAR T cell efficacy in several cancer types.

Introduction
The success of immunotherapy in cancer in recent years has highlighted the potential to utilize a patient’s immune system to eradicate cancer. With adoptive cellular therapy, this conventionally involves ex vivo expansion of a patient’s tumor-infiltrating lymphocytes (TILs) to reinfuse a population of T lymphocytes that contains clones responsive to tumor antigens. While this approach has been successful in melanoma (1), and to a lesser extent in other cancers such as renal cell carcinoma (2) and glioma (3), it is not broadly applicable to multiple cancer types because of the low frequency of TILs within the microenvironment of less immunogenic tumors. To circumvent this problem, a patient’s peripheral blood T lymphocytes can be genetically modified to express a transgenic T cell receptor (TCR) (4) or a chimeric antigen receptor (CAR) (5) to target a known tumor antigen. This approach enables the generation of large numbers of tumor-specific T cells. CARs are composed of a Fab fragment that recognizes a tumor antigen linked to an intracellular domain with the signaling domains of CD3 and CD28 and/or 4-1BB. The incorporation of CD28/4-1BB signaling domains leads to more robust T cell activation and consequently more potent antitumor effects (6–9). CAR T cells have been highly successful in hematological malignancies such as acute lymphoblastic leukemia (10) and chronic lymphoblastic leukemia (11, 12), but their success in solid cancers has been limited to date (13). The reasons for this are not fully understood but include the need to traffic to a solid tumor site (as opposed to hematological disease) and immunosuppression in the local tumor microenvironment. A number of preclinical studies have shown that CAR T cell efficacy can be improved in the solid tumor setting by targeting of tumor immunosuppressive mechanisms (14, 15). Notably, we have previously shown that blockade of PD-1 with a monoclonal antibody can enhance the antitumor activity of CAR T cells (16). Similarly, reversal of PD-1 signaling through a chimeric PD-1/CD28 construct has been shown to enhance CAR T cell function (17). One immunosuppressive pathway that has recently gained attention as a potential target to reverse tumor-induced immunosuppression is the production of adenosine. Adenosine is found at immunosuppressive concentrations within the tumor microenvironment (18) and can be generated from extracellular ATP in a stepwise manner by the ectoenzymes CD39 and CD73 (19). CD73 is expressed on both tumor cells and host immunosuppressive cells such as Tregs and myeloid-derived suppressor cells (MDSCs). CD73 expression has been shown to negatively correlate with patient prognosis in a number of cancer types (20–22), highlighting the relevance of the CD73/adenosine immunosuppressive axis in patients. Furthermore, preclinical studies have shown that targeting of either CD73...
We have previously reported that A$_2$AR blockade synergizes with anti–PD-1 by enhancing endogenous antitumor immune responses (33, 35), and so we hypothesized that this combination may also enhance CAR T cell activity.

Herein, we demonstrate, for the first time to our knowledge, that CAR T cells upregulate A2ARs upon antigen-specific stimulation in vitro and in vivo. Consequently, A2AR-deficient CAR T cells had significantly greater therapeutic efficacy than WT CAR T cells. Moreover, we observed that blockade of A2ARs using 2 distinct pharmacological compounds enhanced the efficacy of CAR T cell responses, particularly in the setting of PD-1 blockade. The effect coincided with increased activation of both CD8$^+$ and CD4$^+$ CAR T cells and was dependent on increased IFN-$\gamma$ production by CAR T cells. Moreover, we show that primary melanomas express both HER2 and CD73 and that A2AR activation limits the efficacy of patient-derived anti-HER2 CAR T cells. Our data strongly suggest that A2AR targeting could be used in combination with CAR T cells and checkpoint blockade to significantly increase the clinical utility of CAR T cells.

or CD39 with either monoclonal antibodies or pharmacological inhibitors can enhance antitumor immunity (23–26). An alternative strategy is to target the downstream adenosine receptors. Adenosine binds to 4 known receptors: A$_1$, A$_2A$ (herein referred to as A$_2$AR), A$_2B$, and A$_3$. Although A$_2B$ and A$_3$ are also expressed on T cells, adenosine is thought to predominantly suppress endogenous antitumor T cell responses through stimulation of A$_2$ARs expressed on activated T cells (18, 23, 24, 27–31). Indeed, A$_2$AR-deficient mice (hereafter referred to as A$_2$AR$^{-/-}$ mice) are resistant to the immunosuppressive effects of adenosine and elicit enhanced antitumor immune responses (18, 27, 32, 33).

Targeting the A$_2$R is a highly translational approach to blocking this axis, since A$_2$AR antagonists have already undergone clinical trials for Parkinson’s disease (34). The potential of targeting this receptor is underlined by the emergence of clinical trials using A$_2$AR antagonists in oncology (ClinicalTrials.gov, NCT02655822). In the current study we investigated whether targeting adenosine-mediated immunosuppression could enhance CAR T cell activity. We have previously reported that A$_2$R blockade synergizes with anti–PD-1 by enhancing endogenous antitumor immune responses (33, 35), and so we hypothesized that this combination may also enhance CAR T cell activity. Herein, we demonstrate, for the first time to our knowledge, that CAR T cells upregulate A$_2$ARs upon antigen-specific stimulation in vitro and in vivo. Consequently, A$_2$AR-deficient CAR T cells had significantly greater therapeutic efficacy than WT CAR T cells. Moreover, we observed that blockade of A$_2$ARs using 2 distinct pharmacological compounds enhanced the efficacy of CAR T cell responses, particularly in the setting of PD-1 blockade. The effect coincided with increased activation of both CD8$^+$ and CD4$^+$ CAR T cells and was dependent on increased IFN-$\gamma$ production by CAR T cells. Moreover, we show that primary melanomas express both HER2 and CD73 and that A$_2$AR activation limits the efficacy of patient-derived anti-HER2 CAR T cells. Our data strongly suggest that A$_2$R targeting could be used in combination with CAR T cells and checkpoint blockade to significantly increase the clinical utility of CAR T cells.
The Journal of Clinical Investigation

RESEARCH ARTICLE

v

931

jci.org   Volume 127   Number 3   March 2017

body that directly stimulates the CAR via a c-myc epitope incor-
porated within the scFv, or anti-CD3/CD28 monoclonal antibodies
as a positive control. These experiments revealed that stimulation
of gene-modified T cells through the CAR results in upregulation
of the A2AR at levels equivalent to those achieved following TCR
stimulation (Figure 1A). To investigate whether this effect was
also observed following recognition of HER2 expressed on tumor
target cells, anti-HER2 CAR T cells were cocultured with either
24JK mouse fibrosarcoma cells, or 24JK cells engineered to express
human HER2 as previously described (ref. 36 and Supplemental
Figure 2A). Coculture with 24JK-HER2 tumor cells significantly
increased A2AR expression on anti-HER2 CAR T cells, confirming
that CAR activation resulted in upregulation of the A2AR (Figure
1B). These data provided a strong rationale to investigate further
the effect of A2AR stimulation on CAR T cell activity.

A2AR blockade enhances the in vitro activity of CAR T cells

Results

Activation of the CAR leads to increased expression of the A2AR.
Although A2AR is known to be upregulated following TCR activation
and consequently suppresses T cell responses, the effect of CAR
stimulation on the expression of A2ARs is not known. Moreover, the
ability of adenosine to suppress CAR T cell responses has not been
investigated. To examine this we first transduced primary murine
splenocytes with a CAR containing the CD28 and CD3ζ signaling
domains recognizing the human HER2 antigen (scFv-CD28-ζ).
Murine splenocytes were activated and retrovirally transduced with
an anti-HER2 CAR. Consistent with our previous results (16), after
7 days of culture in IL-2/IL-7–containing media, the anti-HER2
T cells were predominantly CD8+ T cells (78% ± 4%) with only
a smaller percentage of CD4+ T cells present in the culture (15%
± 4%) (Supplemental Figure 1; supplemental material available
online with this article; https://doi.org/10.1172/JCI89455DS1). To
determine whether activation of the CAR induced upregulation of
the A2ARs, T cells were activated with either an anti-myc tag anti-
body that directly stimulates the CAR via a c-myc epitope incor-
porated within the scFv, or anti-CD3/CD28 monoclonal antibodies
as a positive control. These experiments revealed that stimulation
of gene-modified T cells through the CAR results in upregulation
of the A2AR at levels equivalent to those achieved following TCR
stimulation (Figure 1A). To investigate whether this effect was
also observed following recognition of HER2 expressed on tumor
target cells, anti-HER2 CAR T cells were cocultured with either
24JK mouse fibrosarcoma cells, or 24JK cells engineered to express
human HER2 as previously described (ref. 36 and Supplemental
Figure 2A). Coculture with 24JK-HER2 tumor cells significantly
increased A2AR expression on anti-HER2 CAR T cells, confirming
that CAR activation resulted in upregulation of the A2AR (Figure
1B). These data provided a strong rationale to investigate further
the effect of A2AR stimulation on CAR T cell activity.

A2AR blockade enhances the in vitro activity of CAR T cells

To investigate the functional consequence of A2AR expression, we
determined the cytokine production of CAR T cells following

Figure 2. A2AR is upregulated on CAR T cells in vivo and limits their antitumor efficacy. C57BL/6-HER2 mice were injected with 1 × 10^6 24JK-HER2
tumor cells (subcutaneous) (A) or 1 × 10^5 E0771-HER2 tumor cells (B and D–F). (A, B, D, and E) Mice were injected with 1 × 10^6 CAR T cells derived from WT or A2AR−/−
splenocytes on days 7 and 8 after tumor injection following total-body irradiation (5 Gy) on day 7. Mice were injected with 50,000 IU IL-2 on days 0–4
after T cell transfer and, where indicated, with anti–PD-1 (200 μg/mouse) or 2A3 isotype control on days 0, 4, and 8 after T cell transfer. (C) 1 × 10^6 24JK-
HER2 tumor cells were cocultured with 1 × 10^6 anti-HER2 CAR T cells for 48 hours in the presence of anti–PD-1 (50 μg/ml) or 2A3 isotype control. A further
1 × 10^5 24JK-HER2 tumor cells were added after 24 hours to provide chronic stimulation. Cells were lysed after 48 hours. Expression of A2AR is shown
relative to T cells cocultured with 24JK parental tumor cells. (F) E0771-HER2 tumor-bearing mice were treated as above with Ly5.1+ CAR T cells. Nine days
after T cell transfer, tumors and spleens of tumor-bearing mice were pooled, and CAR (Ly5.1+) and endogenous (CD45.2+) CD8+ T cells were FACS sorted.
Expression of A2AR on these subsets was determined by qPCR in triplicate. (A, B, and D) Data are presented as the mean ± SEM of 6–8 mice from a
representative experiment of n = 3. (C) Data are represented as the mean ± SD from a representative experiment of n = 2. (E) Survival endpoint was when
tumor size reached >100 mm^2. Data are shown for pooled experiments with n = 14–24 per group. *P < 0.05, **P < 0.01, ***P < 0.001 by 2-way ANOVA
(A, B, and D), 1-way ANOVA (C and F), or Mantel-Cox test (E).
was almost fully reversed by the addition of the A2AR antagonist SCH58261 (Figure 1, C and D). Intracellular cytokine staining of anti-HER2 CAR T cells following coculture with 24JK-HER2 tumor cells revealed that NECA significantly suppressed IFN-γ production of both CD8+ and CD4+ CAR T cells (Supplemental Figure 3A).

To more broadly investigate the effect of A2AR activation on CAR T cell function, we investigated the effect of A2AR stimulation on the production of TNF-α, IL-10, IL-2, and IL-4. These experiments revealed that A2AR activation similarly suppressed anti-HER2 CAR T cell production of TNF-α and IL-10 (Figure 1E), while IL-2 and IL-4 were not secreted at detectable levels following coculture with HER2-expressing tumor cells (Supplemental Figure 3B).

Figure 3. A2AR blockade enhances the efficacy of CAR T cells in combination with anti–PD-1 without inducing autoimmune pathology. C57BL/6-HER2 mice were injected with 1 × 10⁶ 24JK-HER2 (subcutaneous) (A) or 1 × 10⁵ E0771-HER2 tumor cells (B–E) and treated with WT CAR T cells and anti–PD-1 or 2A3 per Figure 2. Mice were also treated daily with either 1 mg/kg SCH58261 (A–C), 1 mg/kg ZM241385 (D), or vehicle control (A, B, and D). Data are presented as the mean ± SEM of 6–14 mice. (C) Data are shown for n = 18–28 per group with tumors greater than 100 mm² taken as the cutoff for survival. (E) H&E sections were taken from the cerebellum and breast (non–tumor-inoculated) in E0771-HER2 tumor-bearing mice undergoing therapy at day 9 after T cell injection. Representative sections are shown at an original magnification of ×200. *P < 0.05, **P < 0.01 by 2-way ANOVA (A, B, and D) or Mantel-Cox test (C).
Interestingly, A<sub>2a</sub>R activation had minimal impact on the cytotoxicity of CAR T cells, reflected in the killing of HER2<sup>+</sup> target cells in chromium release assays (Supplemental Figure 4A) or staining for the degranulation marker CD107a (Supplemental Figure 4, B and C). This is consistent with our previous observations on the effects of A<sub>2a</sub>R stimulation on the in vitro cytotoxic function of OVA-specific OT-I T cells (33). To confirm that the effect of NECA on cytokine production was mediated through the A<sub>2a</sub>R, we next measured the levels of IFN-γ and TNF-α produced by WT or A<sub>2a</sub>R<sup>−/−</sup> CAR T cells following antigen stimulation in the presence or absence of NECA. We found that the production of both IFN-γ and TNF-α by anti-HER2 CAR T cells derived from A<sub>2a</sub>R<sup>−/−</sup> mice was not modulated by NECA, confirming the involvement of the A<sub>2a</sub>R in this effect (Figure 1F).

**A<sub>2a</sub>R CAR T cells exhibit superior antitumor function in vivo.**

Given that our in vitro data indicated that CAR T cell function was negatively modulated by A<sub>2a</sub>R stimulation, we next assessed the impact of targeting A<sub>2a</sub>R on CAR T cell activity in vivo. CAR T cell function was tested using the 24JK-HER2 and E0771-HER2 lines, both of which expressed CD73 (Supplemental Figure 2B). Using WT or A<sub>2a</sub>R<sup>−/−</sup> donor T cells transduced with the anti-HER2 CAR, we found that adoptive transfer of A<sub>2a</sub>R<sup>−/−</sup> CAR T cells had significantly greater activity against established subcutaneous 24JK-HER2 tumors (Figure 2A and Supplemental Figure 5A) or E0771-HER2 tumors injected orthotopically in the mammary fat pad of HER2 recipient mice (Figure 2B). Importantly, WT and A<sub>2a</sub>R<sup>−/−</sup> T cells showed equivalent expression of the CAR and similar phenotype in terms of CD4<sup>+</sup> and CD8<sup>+</sup> frequency, indicating that the differences in antitumor efficacy were not due to transduction efficiency (Supplemental Figure 1). Since we have previously shown that A<sub>2a</sub>R blockade enhances anti-PD-1 activity (33) and that anti-PD-1 enhances the efficacy of CAR T cells (16), we next investigated the potential of concomitantly targeting both immunosuppressive pathways. Blockade of PD-1 in vivo in vitro cocultures of anti-HER2 CAR T cells with 24JK-HER2 target cells was shown to enhance A2aR expression (Figure 2C), suggesting that enhanced A<sub>2a</sub>R expression could limit the efficacy of CAR T cells treated with anti-PD-1. Therefore we investigated the efficacy of CAR T cells derived from WT or A<sub>2a</sub>R<sup>−/−</sup> splenocytes in mice bearing established E0771-HER2 tumors and treated with either anti-PD-1 or isotype control. Strikingly, mice treated with A<sub>2a</sub>R<sup>−/−</sup> CAR T cells and anti-PD-1 showed significantly greater therapeutic responses (Figure 2D and Supplemental Figure 5B), resulting in a significant survival advantage in mice treated with this combination (~40%) compared with mice treated with WT CAR T cells and anti-PD-1 (~15%) (Figure 2E). In a further experiment we compared the level of A<sub>2a</sub>R expressed on Ly5.1<sup>+</sup> congenically marked CD8<sup>+</sup> CAR T cells and endogenous CD45.2<sup>+</sup>CD8<sup>+</sup> T cells derived from the tumor and spleen at day 9 following adoptive transfer. We found that A2aR expression was significantly increased in CAR T cells isolated from E0771-HER2 tumors compared with either CAR T cells taken from the spleen or endogenous CD8<sup>+</sup> T cells from the spleen or tumor (Figure 2F). These data suggested that antigen-specific stimulation of CAR T cells in vivo induced upregulation of A<sub>2a</sub>R expressed on these cells and that pharmacological blockade of the A<sub>2a</sub>R pathway may enhance the activity of gene-modified T cells directed against HER2<sup>+</sup> tumors.

**A<sub>2a</sub>R blockade combined with anti-PD-1 leads to stronger antitumor effects of CAR T cells.** To investigate the potential of A<sub>2a</sub>R targeting in a translationally relevant setting, we next tested the ability of the A<sub>2a</sub>R antagonist SCH58261 to enhance the therapeutic activity of CAR T cells either alone or in the context of PD-1 blockade. Interestingly, we found that although SCH58261 had little effect on CAR T cell activity against established 24JK-HER2 (Figure 3A) or E0771-HER2 tumors (Figure 3B) when administered alone with CAR T cells, the A<sub>2a</sub>R antagonist significantly enhanced the activity of CAR T cells when combined with PD-1 blockade, resulting in greater tumor growth inhibition (Figure 3, A and B, and Supplemental Figure 5, C and D) and significantly increased survival of mice (Figure 3C). This increased efficacy of CAR T cells was significantly greater than that seen with anti-PD-1 alone. This result was confirmed using an alternative A<sub>2a</sub>R antagonist, ZM241385, confirming the involvement of the A<sub>2a</sub>R (Figure 3D). Coblockade of both A<sub>2a</sub>R and PD-1 pathways in combination with anti-HER2 CAR T cells was critical for this enhanced antitumor effect, given that neither SCH58261, anti–PD-1, nor the combination modulated tumor growth in the absence of CAR T cells (Supplemental Figure 6). In summary, our data demonstrate that dual blockade of PD-1 and A<sub>2a</sub>R pathways could significantly enhance CAR T cell activity.

**Treatment with CAR T cells and dual blockade of A<sub>2a</sub>R and PD-1 pathways does not cause autoimmunity in tumor-bearing mice.** We have previously reported that the human HER2 antigen is expressed as a self-antigen in the brain (cerebellum) and mammary tissue of HER2 transgenic mice (36). In this model we have previously demonstrated that transfer of CAR T cells directed against the HER2 antigen in combination with anti-PD-1 did not induce pathology to HER2<sup>+</sup> tissue (16). This is likely due to the lower level of HER2 expression found on healthy tissues compared with the tumor cells in this model (36). However, given the significant increase in therapeutic responses observed in our model following CAR T cell transfer and A<sub>2a</sub>R/PD-1 blockade, it remained possible that the combined therapy may have resulted in some level of pathology against normal antigen-positive tissue. Therefore we performed H&E staining of brain and mammary sections from HER2 transgenic mice that were preconditioned and challenged with HER2<sup>+</sup> E0771 tumor before receiving anti-HER2 CAR T cells alone or in combination with anti-PD-1 and the A<sub>2a</sub>R antagonist SCH58261. We also assessed mammary and brain tissue from cohorts of mice treated with A<sub>2a</sub>R<sup>−/−</sup> or WT CAR T cells combined with anti-PD-1. All sections were closely assessed for inflammation potentially induced by increased infiltration of T cells. We observed no evidence of pathology in either brain or mammary sections from HER2 transgenic mice that were treated with anti-HER2 CAR T cells in combination with SCH58261 and anti–PD-1 antibody (Figure 3E) or with A<sub>2a</sub>R<sup>−/−</sup> CAR T cells and anti-PD-1 (data not shown). Therefore the data importantly demonstrate that the functional activity of CAR T cells can be significantly increased, leading to improving therapeutic antitumor responses in the absence of toxicity to normal antigen-expressing tissue.

**Dual targeting of PD-1 and A<sub>2a</sub>R pathways enhances cytokine production by CAR T cells in vivo.** We next investigated whether the increased therapeutic effects associated with concomitant blockade of the PD-1 and A<sub>2a</sub>R pathways correlated with increased function and/or localization of CAR T cells to the tumor site. In
in these experiments we transferred either WT or A2AR–/– anti-HER2 CAR T cells and examined the phenotype and function of tumor-infiltrating CAR T cells, including their cytokine production, frequency, and expression of the proliferative marker Ki-67. Most notably, in the context of PD-1 blockade we observed significantly enhanced IFN-γ produced by CD8+ CAR T cells combined with anti–PD-1 compared with WT CAR T cells and anti–PD-1 as measured by direct ex vivo intracellular staining (Supplemental Figure 7, A and B). Neither TNF-α nor IL-2 could be detected from CAR T cells stained directly ex vivo (data not shown). Direct ex vivo intracellular cytokine staining (without restimulation of T cells) likely underestimates cytokine production, and so we further analyzed this facet of CAR T cells using the more sensitive technique of quantitative PCR (qPCR) on FACS-isolated CD8+ T cells. Strikingly, using this methodology, the increase in IFN-γ mRNA was found to be even more highly significant (P < 0.01), with a more than 25-fold increase in IFN-γ mRNA in A2AR–/– CAR T cells compared with WT controls (Figure 4A). To further assess the cytokine production of CAR T cells within the tumor microenvironment, we also analyzed their ability to produce IFN-γ, TNF-α, and IL-2 following a brief restimulation with PMA and ionomycin. Using this methodology, a significant increase in the percentage of CD8+ CAR T cells producing IFN-γ, TNF-α, and IL-2 was observed in A2AR–/– CAR T cells compared with WT controls (Figure 4B).
CAR T cells expressing IFN-γ was observed in cells isolated from mice treated with A2AR–/– CAR T cells and anti–PD-1 (Figure 4, B and C), thus confirming our results obtained with cells stained directly ex vivo (Supplemental Figure 7, A and B). Strikingly, stimulation of the cells with PMA/ionomycin revealed that a significantly greater proportion of A2AR–/– CAR T cells produced TNF-α compared with WT controls (Figure 4, B and C), and, importantly, the combination of A2AR–/– CAR T cells and anti–PD-1 treatment resulted in a significantly greater proportion of IFN-γ+TNF-α+ double-positive CD8+ CAR T cells (Figure 4, B and C). Interestingly, analysis of the CD4+ CAR T cell population revealed that CD4+ A2AR–/– CAR T cells also exhibited a significantly greater proportion of IFN-γ+TNF-α+ double-positive cells (Figure 4D). PD-1 blockade showed a trend to further enhance this phenomenon, although this was not statistically significant. Even in the presence of PMA/ionomycin stimulation we could not detect the production of IL-2 by CAR T cells ex vivo, in keeping with our earlier in vitro results (Supplemental Figure 3).

Interestingly, A2AR–/– CAR T cells were not found at increased proportion (Supplemental Figure 7C) or absolute cell number (data not shown) compared with WT CAR T cells, and differences in Ki-67 expression were not observed in either CD8+ or CD4+Foxp3– subsets (Supplemental Figure 7D). Therefore the lack of A2AR expression appeared to act predominantly by enhancing the activation of the CAR T cells, particularly in combination with anti–PD-1.

To further investigate the effect of A2AR deficiency on CAR T cell responses in vivo, we investigated the frequency and phenotype of splenic CAR T cells in mice treated with WT or A2AR–/– anti-HER2 CAR T cells.
This revealed a significantly enhanced proportion (Figure 4E) and absolute number (Figure 4F) of CD44+ cells in mice receiving A2AR-/- CAR T cells. This was shown for both CD8+ and CD4+ T cell populations, suggesting that A2AR activation limited the activation and expansion of both subsets. Notably, this supports our previous observation that A2AR activation limits the activation of both CD8+ and CD4+ subsets in vitro (Supplemental Figure 3A) and in the tumor microenvironment (Figure 4, B–D).

We next examined CAR T cell phenotype following treatment of E0771-HER2 tumors in mice treated with anti-PD-1 and/or the A2AR antagonist SCH58261. In these studies we used congenically marked Ly5.1+ CAR T cells to enable isolation and functional characterization of CAR T cells following transfer. Strikingly, we found that the combination of PD-1 and A2AR blockade significantly enhanced IFN-γ production from CD8+ anti-HER2 CAR T cells (Figure 5A). This was a tumor-specific effect, given that there was negligible IFN-γ detected from CAR T cells isolated from the spleen of treated mice. Blocking IFN-γ activity using a neutralizing antibody revealed that the enhanced production of IFN-γ by CAR T cells following anti-PD-1 and SCH58261 treatment was critical to the enhanced therapeutic efficacy observed (Figure 5B). Notably, in the context of IFN-γ neutralization, the combination of anti-HER2 CAR T cells, anti-PD-1, and SCH58261 did not result in any greater inhibition of tumor growth compared with anti-HER2 CAR T cells alone (Figure 5, B and C). Therefore, the benefit of dual PD-1/A2AR blockade was totally abrogated by IFN-γ depletion.

Interestingly, we found that although the overall frequency of CAR T cells (both CD8+ CAR and CD4+ CAR T cells) at the tumor site was significantly increased compared with control LXSN T cells following adoptive transfer, combined PD-1/A2AR blockade had no additional effect on CAR T cell frequency (Supplemental Figure 8). This was also the case for expression of the proliferative marker Ki-67 (Figure 5D). We also analyzed the effect of combination therapy on the tumor-infiltrating host-derived (CD45.2+) T cells. This analysis revealed that although PD-1 blockade enhanced the frequency of endogenous CD8+ T cells, this was not further increased by A2AR blockade (Supplemental Figure 9A). Interestingly, the combination therapy showed a trend to increase IFN-γ production by CD45.2+CD8+ and CD45.2+CD4+ T cells, although this was not statistically significant (Supplemental Figure 9B). We also did not observe any significant enhancement of the expression of the proliferation marker Ki-67 (Supplemental Figure 9C) in endogenous (CD45.2+) CD8+ or CD4+ T cells. Overall, the data strongly suggest that the increased therapeutic effects observed in the HER2 tumor models following A2AR targeting are predominantly due to enhanced CAR T cell activation including increased IFN-γ production following antigen stimulation.

Genetic targeting of A2AR protects CAR T cells from adenosine-mediated immunosuppression. Given the superior antitumor function of CAR T cells derived from A2AR-/- mice, we next investigated whether A2AR knockdown using a retroviral shRNA-driven approach could replicate this phenotype. This is a highly translational approach to reduce the expression of A2AR in CAR T cells and thus augment their function. Using shRNAs directed against A2AR in a retroviral vector, we dual-transduced T cells with the anti-HER2 CAR and A2AR-directed shRNAs or a scrambled shRNA control. At day 4–6 after transduction we selected the transduced cells with 2 µg/ml puromycin, and at day 8 after transduction, anti-HER2 CAR T cells were harvested for mRNA analysis. Significant reduction in the level of A2aR mRNA was observed using 2 distinct A2AR-targeting shRNAs (Figure 6A). We then investigated the effect of A2AR knockdown on the function of CAR T cells. Having previously shown that A2AR activation significantly suppressed CAR T cell IFN-γ production upon coculture with HER2-expressing tumor targets (Figure 1), we assessed the effect of NECA on the ability of CAR T cells to produce IFN-γ following coculture with 24JK-HER2 tumor cells. As expected, NECA significantly inhibited the production of IFN-γ of CAR T cells transduced with a scrambled shRNA (Figure 6B and Supplemental Figure 10). However, NECA no longer suppressed CAR T cells transduced with either of the 2 hairpins directed against A2aR (Figure 6B and Supplemental Figure 10). This result was comparable with that of using CAR T cells derived from A2AR-/- mice (Figure 1) and indicates that knockdown of A2AR is a viable therapeutic strategy to replicate the enhanced antitumor function of A2AR-/- CAR T cells.
As a result of this preclinical work, several pharmaceutical companies have now developed A2AR antagonists for use in oncology, with the first clinical trials being initiated (NCT02655822) (38). The ectoenzymes CD73 and CD39, which catalyze the conversion of ATP into adenosine, are overexpressed in several cancer types (19). Although the association between CD73/CD39 expression and patient prognosis is complex (39), in many cases the expression of CD73 has been shown to negatively correlate with patient survival. This includes patient cohorts in breast (20), ovarian (22), renal cell (40), rectal adenocarcinoma (41), and prostate cancer (42). Furthermore, targeting this pathway has been shown to enhance clinical responses to chemotherapy (20) and other classes of immunotherapy (33, 43, 44). In the current study we explored the possibility that targeting the A2AR could enhance CAR T cell activity. We used CAR T cells targeting human HER2 in transgenic mice engineered to endogenously express human HER2. This allowed us to assess both antitumor activity and potential pathology against normal HER2+ expressing tissues. This is relevant given the lethal toxicity observed in 1 patient treated with anti-HER2 CAR T cells (45). Although the HER2 transgenic model used in this study does not model the pulmonary toxicity observed in this patient, it provides proof of principle that targeting A2AR does not increase CAR T cell responses against HER2+ healthy tissues. Furthermore, a subsequent trial targeting HER2 using lower doses of CAR T cells in a larger cohort of patients reported no severe toxicity (46).

Our investigations revealed that A2AR is upregulated following stimulation of the CAR to an extent similar to that observed with TCR activation. Although the signaling pathways control-
ling A2AR expression have not been fully defined, it has previously been shown that it is upregulated rapidly after TCR activation and is NFAT dependent (47). The A2AR gene also has putative binding sites for AP-1, NF1, and AP-4, although the role for these transcription factors in A2AR expression has not been formally demonstrated (48). Our current study shows that the signaling pathway mediating A2AR upregulation is engaged by the widely used second-generation CAR containing the signaling domains for CD3 and CD28, therefore providing the rationale to investigate whether A2AR blockade could enhance CAR T cell activation. Further studies revealed that A2AR activation suppressed cytotoxic function by CAR T cells in vitro but, interestingly, did not appear to modulate cytotoxic function of CAR T cells. This is consistent with our previous observations regarding A2AR activation of OT-I T cells cocultured with OVA-expressing tumor cells (33). In this study we observed that although OT-I cytotoxic function was not improved by A2AR blockade in vivo, treatment of mice with the A2AR antagonist SCH58261 increased the expression of granzyme B in tumor-infiltrating CD8+ T cells in vivo. Although we were unable to detect changes in the expression of granzyme B in this study (data not shown), this is likely to be a result of the in vitro activation protocol required to generate CAR T cells, which results in more than 90% of CD8+ T cells being granzyme B+. It therefore remains possible that A2AR blockade enhances cytotoxic activity of CAR T cells in vivo.

Our studies showed that CAR T cells derived from A2AR–/– mice exhibit increased potency compared with WT controls. The magnitude of this phenotype was greater than that observed using 2 distinct A2AR antagonists (SCH58261 or ZM241385) in combination with WT CAR T cells. The reasons for this are not fully understood but may relate to incomplete blockade of A2ARs achieved by pharmacological blockade in our studies. Although we achieved superior efficacy by increasing the dose of SCH58261 to 5 mg/kg twice daily, the antitumor response remained less marked than using A2AR–/– CAR T cells (data not shown). While higher dosing of A2AR antagonists is achievable using A2AR compounds in clinical trials such as SYN-115 and CPI-444, A2AR knockdown may represent an alternative or complementary method to enhance CAR T cell function. Indeed, our experiments with A2AR-targeting shRNA highlight the potential for A2AR knockdown to enhance CAR T cell function. These data were generated using transiently transfected HEK293T cells to produce retrovirus. Therefore we are currently unable to generate sufficient CAR T cells to perform an in vivo analysis. Nevertheless, these proof-of-principle studies highlight the potential for A2AR knockdown strategies to enhance CAR T cell function in patients.

With either pharmacological blockade or genetic deficiency of A2AR, the phenotype observed was significantly greater when A2AR targeting was combined with PD-1 blockade. This is consistent with our previous observations using the combination of anti-PD-1 and SCH58261 to significantly enhance endogenous antitumor T cell responses (33). In this previous study we found that PD-1 blockade enhanced A2AR expression on tumor-infiltrating CD8+ T cells, making them more susceptible to A2AR-mediated suppression. Similarly, in the current study we observed that PD-1 blockade enhanced A2AR expression on CAR T cells. Therefore it is likely that this mechanism contributes to the increased efficacy of the combination of PD-1 and A2AR blockade in the context of CAR T cell therapy.

Interestingly, we observed that A2AR targeting enhanced the cytokine production of CD8+ CAR T cells both in vitro and in vivo. Most striking effects were seen on the production of IFN-γ following dual targeting of PD-1 and the A2AR, particularly given that the efficacy of the combination therapy was abrogated in the context of IFN-γ neutralization. This result is consistent with recent reports indicating that the efficacy of checkpoint inhibitors in patients is dependent on IFN-γ signaling (49–51). Our studies also revealed that A2AR-deficient CAR T cells exhibited increased secretion of TNF-α within the tumor microenvironment. The reasons for this remain to be elucidated but could be related to the observation that the cAMP/PKA pathway (the predominant signaling pathway for the A2AR) potently inhibits TNF-α production in macrophages (52). Although our results indicate that increased IFN-γ production is critical for the efficacy of dual PD-1/A2AR targeting, this does not preclude a role for TNF-α in this effect given that TNF-α may act in part to increase IFN-γ production.

Notably, the cytokine production of CD4+ CAR T cells were also enhanced by A2AR blockade. This is potentially important given the previous reports indicating that CD4+ CAR T cells can significantly enhance overall CAR T cell efficacy (53–55). Hence, targeting A2AR may enhance CAR T cell activity in part through augmenting CD4+ CAR T cell responses. Notably, in contrast to conventional CD4+ T cells, CAR CD4+ T cells have the capacity to be activated by tumor cells directly owing to robust tumor-antigen recognition through the CAR. This is supported by the fact that CD4+ CAR T cells produce cytokines directly upon coculture with tumor cells whereas OT-II cells are unable to produce cytokines when cocultured with OVA-expressing tumor cells (our unpublished observations). This difference in terms of activation requirements may be important in terms of adenosine-mediated immunosuppression, since concentrations of adenosine are greatest locally within the tumor (18), and so CD4+ CAR T cells may be more susceptible to adenosine-mediated immunosuppression than endogenous CD4+ T cells. It has previously been shown that stimulation of A2AR on CD4+ T cells can promote generation of a Treg phenotype (56, 57) and suppress a CD4-mediated graft-versus-host disease colitis response (58), but relatively little is known about the effect of A2AR stimulation on CD4+Foxp3+ T cells within the tumor microenvironment.

In summary, this study has highlighted the potential of targeting A2AR-mediated suppression to enhance the activity of CAR T cells, particularly against solid tumors, where the activity of CAR T cells has so far been less impressive and where adenosine-mediated immunosuppression is more prevalent due to the hypoxic environment. This is a highly translational approach, since antagonists for A2AR have undergone phase III clinical trials for Parkinson’s disease and are currently in phase I trials in oncology. Given the increased activity of A2AR–/– CAR T cells and our in vitro data with CAR T cells expressing shRNAs targeting the A2AR, we propose that strategies designed to target A2AR at the genetic level are of interest and may be the subject of further studies. Furthermore, given that our data indicate that the A2AR pathway limits the activity of patient-derived CAR T cells and the emergence and success of clinical trials combining adoptive cell transfer (ACT) with both anti-CTLA-4 (59, 60) and anti-PD-1 (NCT02652455), we believe that clinical trials combining CAR T cells and A2AR blockade are warranted.
Methods

Cell lines and mice. The C57BL/6 mouse breast carcinoma cell line E0771 (Robin Anderson, Peter MacCallum Cancer Centre) (61) and 24JK (Patrick Hwu, NIH, Bethesda, Maryland, USA) (62) were engineered to express truncated human HER2 as previously described (63). Tumor lines were also verified to be mycoplasma negative by Victorian Infectious Diseases Reference Laboratory (Melbourne, Victoria, Australia) by PCR analysis. Tumor cells were grown in RPMI supplemented with 10% FCS, 2 mM glutamine, NEAA, sodium pyruvate, and penicillin/streptomycin. For in vivo experiments, the indicated numbers of cells were resuspended in PBS and injected subcutaneously in a 100-μl volume (male mice; 24JK-HER2) or into the fourth mammary fat pad in a 20-μl volume (female mice; E0771-HER2). C57BL/6 WT mice or C57BL/6 hHER2 mice were bred in house at the Peter MacCallum Cancer Centre. C57BL/6 Aβ R−/− mice were bred at St Vincent’s Hospital (Melbourne, Victoria, Australia). Ly5.1 mice used for the adoptive transfer of congenically marked T cells were purchased from the Walter and Eliza Hall Institute (Melbourne, Victoria, Australia). Mice were used between 6 and 16 weeks of age.

Antibodies, cytokines, agonists, and antagonists. SCH58261, ZM241385, and 5’-(N-ethylcarboxamido)adenosine (NECA) were purchased from Sigma-Aldrich. Antibodies to PD-1 (clone RMP1-14) or isotype control (clone 2A3) were purchased from BioXcell. For cell stimulation, anti-CD3 (clone 145-2C11) and anti-CD28 (clone 37B3) antibodies were purchased from BD Pharmingen and anti-myc tag (clone 2276) from Cell Signaling Technology. IL-2 and IL-7 used for T cell stimulation were purchased from R&D Systems and filtered (0.45-μm filter) at days 2 and 3 after transfection and used to transduce murine splenocytes concurrently with the anti-HER2 CAR-encoding retrovirus. Three days after transduction, T cells were selected using 2 μg/ml puromycin.

Analysis of adenosine receptor expression by reverse transcriptase PCR. RNA was isolated from T lymphocytes using the Qiagen miRNA Easy Mini Kit per the manufacturer’s instructions. cDNA was generated and qPCR analysis for L32, IFN-γ, and A2aR was determined as previously described (32, 33).

Treatment of tumor-bearing mice. C57BL/6 human HER2 transgenic mice were injected subcutaneously with 1 × 10⁶ 24JK-HER2 cells or subcutaneously/orthotopically with 1 × 10⁶ E0771-HER2 cells. At day 7 after tumor injection, mice were preconditioned with total-body irradiation (5 Gy) prior to the administration of 1 × 10⁶ CAR T cells on days 7 and 8. Mice were also treated with 50,000 IU IL-2 on days 0–4 after T cell transfer. Mice were treated with either isotype control (2A3) or anti-PD-1 (200 μg per mouse) on days 0, 4, and 8 after T cell transfer and with 1 mg/kg SCH58261, 1 mg/kg ZM241385, or vehicle control daily.

Analysis of tumor-infiltrating immune subsets. Tumors were excised and digested postmortem using a cocktail of 1 mg/ml collagenase type IV (Sigma-Aldrich) and 0.02 mg/ml DNase (Sigma-Aldrich). After digestion at 37°C for 30 minutes, cells were passed through a 70-μm filter twice. Cells were then analyzed for various functional parameters including cytokine production by flow cytometry directly ex vivo as previously described (32). In some experiments, isolated cells were restimulated with PMA (10 ng/ml) and ionomycin (1 μg/ml; Sigma-Aldrich) in the presence of GolgiPlug and GolgiStop (BD Biosciences) for 4 hours before flow cytometry analysis.

Generation of human CAR T cells. Primary patient melanomas were resected, and 2-mm³ pieces of tissue were cultured in T cell media supplemented with 10% human serum (Valley Biomedical) and 6,000 IU/ml IL-2 until T cells were expanded to 100 × 10⁶ cells, at which point they were frozen down. After thawing, T cells were rested overnight in IL-2–containing media (3,000 IU/ml) and then stimulated with soluble anti-CD3 (OKT3; 30 ng/ml) and 3,000 IU/ml IL-2 in the presence of irradiated (50 Gy) allogeneic feeder peripheral blood mononuclear cells. Six days after activation, T cells were transduced using supernatant from the packaging line PG13-anti-HER2 CD28/CD3ζ as previously described (32). Transduction was performed as for mouse splenocytes but at a cell density of 2.5 × 10⁶ per well in 5 ml total volume. Transduced T cells were selected using G418 (50 μg/ml) and analyzed by flow cytometry day 5 after selection. T cells were maintained in IL-2–containing media (600 IU/ml) with further rounds of anti-CD3/anti-CD28 stimulation used when required to increase T cell numbers.

Generation of matched primary melanoma cell lines. Tumor tissue was verified as melanoma in origin via positive staining for SOX10 and S100B. Tumors were digested in a mixture of 1 mg/ml collagenase type IV (Sigma-Aldrich), 0.02 mg/ml DNase (Sigma-Aldrich), and gentamicin (10 μg/ml). Primary melanoma cell lines were established in RPMI supplemented with 10% FCS, GlutaMAX (Gibco), and penicillin/streptomycin, and, when necessary, passaged through NSG mice. Established melanoma lines were stained for S100B to reverify their status as melanomas.

Statistics. Statistical tests were performed as indicated in the figure legends with a P value less than 0.05 considered significant.

Study approval. All animal studies were approved in advance by the Peter MacCallum Animal Ethics and Experimentation Commit-
Author contributions
PAB and PKD designed the experiments and wrote the manuscript. PAB, MAH, LG, and PKD analyzed the data. PAB, MAH, LG, JKM, KS, AJD, LBJ, SM, CYS, and PKD performed the experiments. JKM and DG collected patient materials. MHK provided critical reagents. MAH, LG, RSC, RWJ, JAT, JS, SL, LG, DK, and MHK provided intellectual input and read the manuscript.

Acknowledgments
The authors acknowledge the assistance of the Animal Facility technicians at the Peter MacCallum Cancer Centre. This work was funded by Project and Program grants from the National Health and Medical Research Council (NHMRC, APP1062580, APP1122444), a Cancer Council Victoria Project Grant (APP1084420), and a grant from the Peter MacCallum Cancer Centre Foundation. PAB and CYS are supported by National Breast Cancer Foundation Fellowships (ID nos. PF-14-008 and ECF-16-005). PKD and MHK are supported by NHMRC Senior Research Fellowships (APP1041828 and APP1058388, respectively). RWJ is supported by a Senior Principal Research Fellowship from the NHMRC.

Address correspondence to: Paul A. Beavis or Phillip K. Darcy, Cancer Immunotherapy Laboratory, Victorian Comprehensive Cancer Centre, 305 Grattan Street, Melbourne, Victoria 3000, Australia. Phone: 613.85595051; E-mail: paula.beavis@petermac.org (PAB); phil.darcy@petermac.org (PKD).

5. Eshhar Z, Waks T, Gross G, Schindler DG. Chimeric receptors providing both primary and costimulatory signaling in T cells from a single AN. Chimeric receptors providing both primary and T-cell receptors.