Citation for final published version:


Please note:
Changes made as a result of publishing processes such as copy-editing, formatting and page numbers may not be reflected in this version. For the definitive version of this publication, please refer to the published source. You are advised to consult the publisher’s version if you wish to cite this paper.

This version is being made available in accordance with publisher policies. See http://orca.cf.ac.uk/policies.html for usage policies. Copyright and moral rights for publications made available in ORCA are retained by the copyright holders.
A Critical Role for OX40 in T Cell–mediated Immunopathology during Lung Viral Infection

Ian R. Humphreys,1 Gerhard Walzl,1 Lorna Edwards,1 Aaron Rae,1 Sue Hill,2 and Tracy Hussell1

1Centre for Molecular Microbiology and Infection (CMMI), Biological Sciences, Imperial College of Science, Technology and Medicine, London SW7 2AZ, United Kingdom
2Xenova Research Ltd., Cambridge CB4 0WG, United Kingdom

Abstract

Respiratory infections are the third leading cause of death worldwide. Illness is caused by pathogen replication and disruption of airway homeostasis by excessive expansion of cell numbers. One strategy to prevent lung immune–mediated damage involves reducing the cellular burden. To date, antiinflammatory strategies have affected both antigen-specific and naive immune repertoires. Here we report a novel form of immune intervention that specifically targets recently activated T cells alone. OX40 (CD134) is absent on naive T cells but up-regulated 1–2 d after antigen activation. OX40–immunoglobulin fusion proteins block the interaction of OX40 with its ligand on antigen-presenting cells and eliminate weight loss and cachexia without preventing virus clearance. Reduced proliferation and enhanced apoptosis of lung cells accompanied the improved clinical phenotype. Manipulation of this late costimulatory pathway has clear therapeutic potential for the treatment of dysregulated lung immune responses.

Introduction

According to the World Health Organization lower respiratory tract infections are the third most common cause of death (1). Influenza virus is a causative agent of both epidemic and pandemic respiratory viral illness with over 26,000 deaths attributed to the last outbreak in Britain alone (2). Though pivotal for viral clearance, over exuberant T cell responses result in airway occlusion (3, 4) and contribute significantly to pathology (5). Therefore, in the absence of universal vaccine candidates, inhibition of inflammatory T cells presents a novel strategy for therapeutic intervention in the treatment of influenza virus infection.

Several processes could be inhibited to thwart T cell proliferation including a reduction of antigen presentation by MHC, inhibition of costimulatory B7 molecules, or depletion of T cells themselves. Such strategies, however, affect both bystander and antigen-activated T cell repertoires. A more definitive approach would selectively inhibit only those T cells recently activated by antigen. OX40 (CD134) is an ideal candidate because unlike CD28, it is absent on naive T cells but up-regulated 1–2 d after antigen encounter (6). OX40 imparts a survival signal to the T cell preventing activation-induced cell death (7) but up-regulating anti-apoptosis gene expression (8) and cytokine production (9). Similarly, OX40 ligand (OX40L) is expressed only at low levels on resting APCs and is up-regulated after CD40–CD40L interactions (6, 10).

The critical role for OX40 is revealed in OX40-deficient mice where CD4+ T cell responses are abrogated during both Th1-driven responses to viral infection (11) and Th2-dominated allergic inflammation (12). Furthermore, inhibition of OX40 using soluble OX40 fusion proteins or antibody abrogates the detrimental effects of colitis in SCID mice (13), inflammatory bowel disease (14), and allergic encephalomyelitis (15).

Manipulation of this late costimulatory pathway has not been tested during virus-induced inflammation. We show that interruption of OX40/OX40L with an OX40–Ig fusion protein ameliorates influenza-driven T cell immunopathology and associated illness without preventing viral clearance. This beneficial outcome is directly linked to a reduced inflammatory infiltrate caused by an inhibition of proliferation.
and enhanced apoptosis. These findings show that OX40 costimulation plays a pivotal role in immunopathology to respiratory viral infection and highlights a novel therapeutic approach for the treatment of influenza-induced disease.

Materials and Methods

Mice and Virus. 8–12-wk-old female BALB/c (Harlan Olac Ltd.) were kept in pathogen-free conditions according to Home Office guidelines. Influenza A strain X31 (hemagglutinin [HA] titre 1024) was provided by A. Douglas (National Institute for Medical Research, London, United Kingdom).

Production of OX40 Fusion Proteins. The generation of murine OX40–mIgG1 fusion protein (OX40–Ig) and the OX40–IgG4 fusion protein containing a mutation of Leu (235) to Glu in the Fc region of IgG4 has been previously described (15, 16). Constructs were deemed LPS-free by gas chromatography-mass spectrometry of fatty acid methyl esters. In brief, samples were derivatized using methanolic HCl and resulting fatty acid methyl esters dissolved in hexanes before column injection on a Stabilwax column (30 m × 0.25 mm internal diameter; Restek Corp.). Samples were analyzed using a temperature gradient of 150–250°C at a rate of 3°C/min. Characteristic retention times and spectra of known standards were used to identify any fatty acid methyl esters present in the samples.

Mouse Infections and Treatment. On day 0 mice were anesthetized and intranasally infected with 50 HA units influenza virus. Mice were injected i.p. with 100 µg OX40–Ig fusion protein (Xenova Pharmaceuticals) or mouse IgG (Caltag) on alternate days. The weight of mice was monitored daily and expressed as percent of original body weight (left axis). Results represent mean values ± SEM from each mouse per group. BAL (B and C) and MLNs (D and E) were removed from influenza-infected mice and cells were stained with OX40–IgG4 or OX40–Ig fusion protein containing a mutation of Leu (235) to Glu in the Fc region of IgG4 has been previously described (15, 16). Constructs were deemed LPS-free by gas chromatography-mass spectrometry of fatty acid methyl esters. In brief, samples were derivatized using methanolic HCl and resulting fatty acid methyl esters dissolved in hexanes before column injection on a Stabilwax column (30 m × 0.25 mm internal diameter; Restek Corp.). Samples were analyzed using a temperature gradient of 150–250°C at a rate of 3°C/min. Characteristic retention times and spectra of known standards were used to identify any fatty acid methyl esters present in the samples.

Mouse Infections and Treatment. On day 0 mice were anesthetized and intranasally infected with 50 HA units influenza virus. Mice were injected i.p. with 100 µg OX40–Ig fusion protein (Xenova Pharmaceuticals) or mouse IgG (Caltag) on alternate days. The weight of mice was monitored daily and expressed as percent of original body weight (left axis). Results represent mean values ± SEM from each mouse per group. BAL (B and C) and MLNs (D and E) were removed from influenza-infected mice and cells were stained with OX40–IgG4 or OX40–Ig fusion protein containing a mutation of Leu (235) to Glu in the Fc region of IgG4 has been previously described (15, 16). Constructs were deemed LPS-free by gas chromatography-mass spectrometry of fatty acid methyl esters. In brief, samples were derivatized using methanolic HCl and resulting fatty acid methyl esters dissolved in hexanes before column injection on a Stabilwax column (30 m × 0.25 mm internal diameter; Restek Corp.). Samples were analyzed using a temperature gradient of 150–250°C at a rate of 3°C/min. Characteristic retention times and spectra of known standards were used to identify any fatty acid methyl esters present in the samples.

Mouse Infections and Treatment. On day 0 mice were anesthetized and intranasally infected with 50 HA units influenza virus. Mice were injected i.p. with 100 µg OX40–Ig fusion protein (Xenova Pharmaceuticals) or mouse IgG (Caltag) on alternate days. The weight of mice was monitored daily and expressed as percent of original body weight (left axis). Results represent mean values ± SEM from each mouse per group. BAL (B and C) and MLNs (D and E) were removed from influenza-infected mice and cells were stained with OX40–IgG4 or OX40–Ig fusion protein containing a mutation of Leu (235) to Glu in the Fc region of IgG4 has been previously described (15, 16). Constructs were deemed LPS-free by gas chromatography-mass spectrometry of fatty acid methyl esters. In brief, samples were derivatized using methanolic HCl and resulting fatty acid methyl esters dissolved in hexanes before column injection on a Stabilwax column (30 m × 0.25 mm internal diameter; Restek Corp.). Samples were analyzed using a temperature gradient of 150–250°C at a rate of 3°C/min. Characteristic retention times and spectra of known standards were used to identify any fatty acid methyl esters present in the samples.

Cell Recovery and Flow Cytometry. Single cell suspensions from bronchoalveolar lavage fluid (BAL), lung tissue, and mediastinal LNs (MLNs) were stained for surface markers and intracellular cytokines and analyzed by flow cytometry as previously described (17). All antibodies were purchased from BD Biosciences except anti–OX40-FITC (Serotec). Influenza-specific CD8⁺ T cells were identified using an APC-labeled MHC class I tetramer (H-2K) loaded with the immunodominant peptide TYQR-TRALV from the influenza nucleoprotein (National Institute of Allergy and Infectious Diseases Tetramer Facility). For apoptosis analysis, binding of PE-labeled annexin V was detected according to the manufacturer’s instructions. All data were acquired on a FACSCalibur™ and 30,000 lymphocyte events were analyzed with CELLQuest™ Pro software (BD Biosciences).

Figure 1. Influenza infection induces weight loss, pulmonary inflammation, and OX40 expression by T cells. (A) Mice were infected with influenza, BAL removed 2, 4, 7, and 11 d after virus challenge. Homogenized cells were freeze thawed three times, centrifuged at 4,000 g, and supernatants were titrated in doubling dilutions on Madin Darby canine kidney cell monolayers in flat-bottomed 96-well plates. After incubation at RT for 3 h, samples were overlaid with methylcellulose and incubated for 72 h at 37°C. Cell monolayers were washed and incubated with anti-influenza antibody (Sero tec), followed by anti–mouse–horseradish peroxidase (Dako Cytomation) and infected cells were detected using 3-aminobenzidine (AEC; Sigma-Aldrich). Infectious units were
Results and Discussion

OX40–Ig Treatment Reduces Influenza-induced Weight Loss and Exuberant T Cell Inflammation During Infection. Intranasal influenza virus infection results in rapid accumulation of lymphocytes within the lung and airways (4). Maximal T cell expansion at 7 d coincides with peak weight loss (Fig. 1 A). The association between cellular infiltration and weight loss is characteristic of many lung viral infections (19, 20). The kinetics of OX40 expression by BAL CD4+ (Fig. 1 B) and CD8+ (Fig. 1 C) T cells followed a similar pattern in that the highest proportion was present 4 d after influenza infection. This profile was also evident in the lung (unpublished data). By calculating the total number of CD4+ OX40+ and CD8+ OX40+ T cells the highest numbers coincided with maximum weight loss at day 7. OX40 expression was also present in the lung-draining MLN. The proportion and total numbers of OX40-expressing CD4+ (Fig. 1 D) and CD8+ (Fig. 1 E) T cells peaked at 4 d.

Because excess T cell infiltration into the virally infected lung compromises lung function and compliance, we next examined the effect of reducing T cell costimulation via OX40. Control-treated mice lost >25% of their initial body weight, whereas those treated with OX40–Ig did not (Fig. 2 A). Visual inspection revealed that control-treated, influenza-infected mice, especially at day 6, appeared hunched, immobile, and severely cachexic, whereas OX40–Ig-treated mice were consistently indistinguishable from uninfected controls (Fig. 2 B). The striking elimination of weight loss and illness severity was accompanied by a reduction in pulmonary inflammation including neutrophils (unpublished data) and CD4+ and CD8+ T cells (Fig. 2 C). The total number of OX40-expressing T cells was also reduced in line with the general reduction in inflammation (unpublished data). However, the percent of T cells expressing OX40 was unaffected. This was not surprising because OX40 expression is induced by CD28 and TCR signals and does not rely on interaction with OX40L. OX40L expression has been observed on some T cells cultured in vitro (21). Although reduced T cell numbers in our study may reflect depletion after OX40–Ig binding, we do not believe this to be the case because OX40–Ig did not enhance T cell death in vitro (unpublished data) and an alternative OX40–Ig fusion that does not fix complement or promote ADCC produced an identical effect (Fig. 2 D). The benefit of manipulating OX40 costimulation is clearly evident in hematoxylin and eosin–stained sections of lung tissue. Cellular infiltration around the airways and blood vessels was markedly reduced in OX40–Ig-treated mice compared with control IgG–treated mice (Fig. 2, E and F, respectively).

Using flow cytometry and intracellular cytokine staining, the number and proportion of CD8+ T cells producing TNF were found to be reduced in OX40–Ig-treated mice (Fig. 3, A and B). Tetramer-binding CD8+ T cells (Fig. 3, C and E) and their production of TNF (Fig. 3 D) were severely reduced by OX40–Ig treatment. Although TNF is greatly increased systemically in some viral infections, we did not observe elevated serum TNF by ELISA or cytokine bead array after influenza virus infection (unpublished data). Anti-TNF antibodies reduce weight loss and cell recruitment during influenza infection (5). Precisely...
how this works, however, is unclear. Influenza virus replication is restricted to the respiratory epithelium. In this situation we believe that TNF indirectly causes weight loss by enhancing cell recruitment and proliferation leading to airway occlusion. These results imply that OX40 signaling plays a critical role during T cell–mediated immunopathology elicited by influenza infection.

Delayed OX40–Ig Treatment Inhibits Weight Loss in Influenza-infected Mice with Established Illness and Does Not Affect Viral Clearance or Recall Responses. Next, we delayed OX40–Ig treatment during influenza virus infection until the mice had lost 20% of their original weight. Such delayed treatment still reversed the decline of weight compared with controls (Fig. 4 A; P < 0.05 days 5–7) and mice appeared perfectly healthy. Plaque assays performed on lung homogenates in a time course study did not reveal any delay in influenza virus clearance when OX40–Ig was administered on day 0 (Fig. 4 B) or 3 d after infection (unpublished data).

The rather surprising lack of an effect of OX40–Ig on virus clearance might be partially explained by stimulation of B cells. OX40 interaction with OX40L imparts a bidirectional signal to the T cell and the APC (22). Although soluble OX40 fusion proteins reduce the signal to the T cell, signaling to the APC remains intact and may even be enhanced. OX40–Ig treatment may therefore induce anti-
viral antibodies and elicit compensatory effects. However, analysis of influenza-specific antibody 4, 7, 11, 15, and 19 d after infection showed no differences in nasal IgA responses or serum IgG1 and IgG2a (unpublished data).

The ability of mice to respond to reinfection was not affected by OX40–Ig treatment despite the significant reduction in T cell immunity during the first infection. A time course analysis after rechallenge did not reveal any statistical differences between the numbers of CD4⁺ (Fig. 4 C) or CD8⁺ (Fig. 4 D) T cells and those binding MHC class I tetramer (Fig. 4 E). In both OX40–Ig–treated and control mice influenza virus was cleared 5 d after rechallenge. On day 2, virus titres were similar (1,080 ± 288 for control and 1,546 ± 246 plaque-forming units/lung in the OX40–Ig–treated group). The lack of an effect on recall responses is surprising and may suggest that sufficient immune memory was generated during the first infection. Influenza virus promotes a very large inflammatory response. It is likely that not all of the inflammatory cells are required to contain infection. The reduced inflammatory infiltrate may therefore still contain enough cells to seed the memory pool. No studies to date have addressed the number of antigen-specific cells required to eliminate a viral infection. In this study we show that a threefold reduction in T cells remains efficient and does not cause disease. Alternatively, efficient rechallenge responses may reflect recruitment of naive cells or the fact that OX40–Ig treatment was only administered to day 10 during the first infection. After day 10 some memory T cell responses may have been generated.

Impaired T Cell Responses in OX40–Ig–treated Mice Is a Consequence of Reduced Proliferation and Enhanced Apoptosis. The reduction of T cells by OX40–Ig could represent reduced proliferation or increased apoptosis. Rather than artificially examining proliferation in vitro, we gave mice BrdU in their drinking water during infection. BrdU is incorporated into proliferating cells and can be detected by flow cytometry using an anti-BrdU antibody. Analysis of MLN cells 4 d after infection revealed that OX40–Ig treatment had significantly reduced both CD4⁺ and CD8⁺ T cell proliferation (Fig. 4 F). This effect was only observed at the peak of proliferation and not during the later stages of infection (unpublished data).

OX40 binding to its ligand induces the anti-apoptotic proteins Bcl-2 and Bcl-xL (8) and prevents activation-induced cell death (23). Reduced T cell numbers in OX40–Ig–treated mice may therefore result from increased cell death. The frequency of apoptotic CD4⁺ and CD8⁺ T cells was identified by annexin V staining and flow cytometry. Administration of OX40–Ig significantly enhanced the proportion of apoptotic CD4⁺ (Fig. 4 G) but not CD8⁺ T cells (unpublished data) in the airways during the later stages of infection (days 7 and 10), implying that OX40 costimulation is required to prolong pulmonary T cell survival.

The reduction in T cell infiltrate is similar to that observed in influenza–infected OX40⁻/⁻ mice (11). Using such mice it is difficult to ascertain whether the improved outcome is due to reduced T cell function or an alteration of APC activation through OX40L. Our studies compliment and extend this in several important ways: (a) we show that both CD4⁺ and CD8⁺ T cells are affected, (b) that inflammatory cytokines are reduced, and (c) that proliferation is reduced and cell death increased.

The reduction of both T cell numbers and proinflammatory cytokine secretion after OX40–Ig treatment raises the question of why lung viral replication is still effectively controlled? There are three plausible explanations: (a) innate immune mechanisms such as NK cells, which were not affected by OX40–Ig treatment (unpublished data), may mediate viral clearance. However, the role of NK cells in immunity to influenza virus infection is unclear. Increased susceptibility to influenza virus in the senescence-accelerated mouse is associated with impaired activity of NK cells, but CD8⁺ T cells are also defective in this model (24). (b) Influenza virus is highly inflammatory and a moderate reduction in the vigor of the inflammatory response might be beneficial without affecting virus clearance. This hypothesis is consistent with the efficient control of other viruses in OX40 knockout mice (25, 11). (c) Because OX40 is expressed 1–2 d after antigen activation, influenza virus infection might be controlled by earlier T cell–APC interactions.

The delayed expression of OX40 makes it an ideal target during immunopathological conditions because it enables initial T cell priming and containment of viral replication. In contrast, blockade of CD28, which is constitutively expressed by T cells, significantly delays influenza clearance (26). The lung microenvironment requires careful immune homeostasis. Excessive inflammation compromises gaseous exchange by occluding the airways and inducing mucus production. This is more apparent in the lungs than other mucosal sites. The gut, for example, can accommodate relatively large cell numbers while retaining its primary function. Evidence from murine models suggests that a reduction, but not elimination, of the lung inflammatory infiltrate is beneficial. Depletion of inflammatory cytokines (5), CD4⁺ or CD8⁺ T cells, or T cell subsets (27) all reduce weight loss without preventing virus clearance. Collectively, this implies that the problem is caused by the number of T cells present and not their phenotype. Manipulation of OX40 therefore presents a novel therapeutic strategy for treatment of immunopathological conditions by reducing the number of activated T cells while leaving the naive repertoire intact.

The authors would like to thank Paul Hitchen (Imperial College London) for help with determining the LPS content of OX40L–Ig fusion proteins, Lorraine Lawrence (Department Leukocyte Biology, Imperial College) for processing of samples for analysis of BrdU, and Professor Ita Askonas for critical review of the manuscript.

This work was supported by The Medical Research Council and The National Asthma Campaign.

Submitted: 3 March 2003
Revised: 19 August 2003
Accepted: 16 September 2003
References