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Ag85A-specific CD4+ T cell lines derived after boosting BCG-vaccinated cattle with Ad5-85A possess both mycobacterial growth inhibition and anti-inflammatory properties

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ABSTRACT
There is a need to improve the efficacy of the BCG vaccine against human and bovine tuberculosis. Previous data showed that boosting bacilli Calmette-Guerin (BCG)-vaccinated cattle with a recombinant attenuated human type 5 adenovirally vectored subunit vaccine (Ad5-85A) increased BCG protection and was associated with increased frequency of Ag85A-specific CD4+ T cells post-boosting. Here, the capacity of Ag85A-specific CD4+ T cell lines – derived before and after viral boosting – to interact with BCG-infected macrophages was evaluated. No difference before and after boosting was found in the capacity of these Ag85A-specific CD4+ T cell lines to restrict mycobacterial growth, but the secretion of IL-10 in vitro post-boost increased significantly. Furthermore, cell lines derived post-boost had no statistically significant difference in the secretion of pro-inflammatory cytokines (IL-1β, IL-12, IFNγ or TNFα) compared to pre-boost lines. In conclusion, the protection associated with the increased number of Ag85A-specific CD4+ T cells restricting mycobacterial growth may be associated with anti-inflammatory properties to limit immune-pathology.

1. Introduction
Bovine tuberculosis (bTB), caused mainly by Mycobacterium bovis, poses economical, animal welfare and human health problems [1]. Development of vaccines for cattle, to be used in conjunction with current regulations, is part of control and eradication strategies for England and Wales for controlling bTB [2,3].

Cattle vaccinated with the live attenuated M. bovis bacillus Calmette-Guerin (BCG) and boosted with adenovirus type 5 (Ad5) expressing Mycobacterium tuberculosis Ag85A (Ag85A) (Ad5-Ag85A) showed improved protection against pathology associated with M. bovis [4,5]. Recently, we adapted the use of the antigen-unbiased T cell expansion method from Geiger et al. [6] to the bovine system [7]. This approach avoids initial in vitro bias caused by expansion of T cell lines by specific repeated cycles of antigen stimulation. We reported that boosting BCG-vaccinated cattle with Ad5-85A increased the frequency of Ag85A-specific CD4+ T cell lines, which correlated with protection, but there was no change in T-cell antigen avidity or epitope-recognition repertoire; the avidity of Ag-85A specific CD4+ T cells was not modulated by viral boosting [7]. Therefore, it was of interest to further characterise the functional properties of these Ag85A-specific CD4+ T cell lines derived from BCG-primed and Ad5-85A-boosted cattle.

In this study, the capacity of these Ag85A-specific CD4+ T cells – generated either before or after Ad-85A boost – to control mycobacteria in vitro and their cytokine profile, after culture for 24 h with BCG-infected macrophages, have been evaluated. Our data suggest that boosting BCG with Ad5-85A enhances protection by increasing the number of Ag85A-specific CD4+ T cells capable of controlling mycobacteria, whilst also potentially developing anti-inflammatory properties to limit immune-pathology.

2. Materials and methods

2.1. Animals

Experiments were carried out according to the UK Animal (Scientific Procedures) Act 1986 under project license PPL70/7737. The study protocol was approved by the APHA Animal}

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Use Ethics Committee (UK Home Office PCD number70/6905) and has been reported previously [5]. Briefly, all animals were vaccinated with $1 \times 10^6$ Colony Forming Units (CFU) M. bovis BCG Danish 1331 subcutaneously at week (wk) 0; Ad5-85A boosted cattle were inoculated at wk 8 with $2 \times 10^8$ infectious units of Ad5-85A by intradermal injection on the shoulder; all animals were challenged endobronchially with $2 \times 10^5$ CFU M. bovis strain at wk 12[5]. Peripheral blood mononuclear cells (PBMC) were cryo-preserved pre- (wk 8) and post-boost (wk 11) and used to generate CD4$^+$ T cell lines. The present study utilised Ag85A-specific CD4$^+$ T cell lines, from three BCG-primed Ad5-85A-boosted cattle and one BCG-vaccinated control, acquired in the study described previously [7].

2.2. Isolation and selection of pre-/post-boost Ag85A-specific CD4$^+$ T cell lines

Polyclonal CD4$^+$ T cell libraries were generated from pre-boost (wk 8) and post-boost (wk 11) PBMC using a method adapted from Geiger et al. [6], as described previously [7]. Ag85A-specific CD4$^+$ T cells were identified by screening the different polyclonal cell cultures for their capacity to proliferate using $1 \times 10^5 - 2 \times 10^5$ CD4$^+$ T cells per culture and 5 µg/ml (initial screening) or 10 µg/ml (subsequent screening) recombinant Ag85A (Lionex GmbH, Germany) and $5 \times 10^5$ CD14$^+$ as antigen presenting cells per well of 96-well U-bottom plates. Ag85A-specific CD4$^+$ T cell lines were expanded, after each 11 day Ag85A-selective culture, using 1 µg/ml lectin from Phaseolus vulgaris leucoagglutinin PHA-L (PHA – Sigma-Aldrich) in the presence of 10 U/ml recombinant human interleukin 2 (Gentaur, Belgium) and CD14$^+$ feeder cells for nine days and cryopreserved. All Ag85A-specific CD4$^+$ T cell lines used in these experiments had undergone three sequential rounds of Ag85A-PHA stimulation.

2.3. Bovine monocyte/macrophage cell culture

Autologous bovine CD14$^+$ (monocytes) or granulocyte-macrophage colony stimulating factor (GM-CSF)-matured CD14$^+$ cells (macrophages [M$\mu$]) were cultured at 37 °C (5% CO$_2$) in complete medium consisting of RPMI 1640 containing 2 mM GlutaMax, 25 mM HEPES, 0.1 mM non-essential amino acids, $5 \times 10^{-5}$ M β-mercaptoethanol, 50 µg/ml Gentamicin (all from Life Technologies, UK), and 10% foetal calf serum (FCS) (Sigma-Aldrich, UK) (complete medium). For M$\mu$ differentiation, monocytes were cultured at a density of $1 \times 10^6$/ml in medium containing recombinant bovine GM-CSF diluted 1/100 (Bio-rad, UK) for six days in Corning Ultra-low adhesion flasks (Sigma-Aldrich); cells were fed GM-CSF on day three. After six days, M$\mu$ were harvested by incubating flasks

![Fig. 1.](image-url) Characterisation of CD14$^+$ cell-derived mature macrophage phenotype. Representative plots of CD14$^+$ cells matured into macrophages (M$\mu$) by culturing in medium supplemented with GM-CSF for six days as described in materials and methods. Harvested M$\mu$ were selected based on their large FSC/SSC phenotype and live M$\mu$ were analysed for CD11c, CD11b and MHC class II (DQ) as described. Plots shown were derived from GM-CSF-matured CD14$^+$ obtained from a cow infected naturally with M. bovis that was used to develop the methodology.
in ice for 20–30 min and washed. Fig. 1 shows a representative immune phenotype profile of GM-CSF matured cells, which defines their surface phenotype as CD11b+CD11c+BoLA-DQ+, which is consistent with GM-CSF matured CD14+/bone-marrow-derived cells [8,9]. Mφ were labelled with the following murine monoclonal antibodies (mab): mAb CC158 (Bio-rad), against bovine MHC class II (DQ), conjugated to Fluorescein using the Zenon labelling kit (Innova Biosciences, UK); IL-A16 (a kind gift from Dr Jan Naessens, ILRI, Nairobi, Kenya) against bovine CD11c, conjugated to R-Phycoerythrin using the Zenon labelling kit (Life Technologies); and mAb CC94, to bovine CD11b, conjugated to Alexa Fluor 700 using the Zenon labelling kit (Life Technologies). Labelled cells were acquired in a CyAn ADP cytometer (Beckman Coulter, UK) using Summit 4.3 (Beckman Coulter) and analysed with FlowJo 7.6.5 (TreeStar, USA). Live cells for analysis were selected based on their FSC/SSC profile and stain pattern with LIVE/DEAD Fixable Violet Dead Cell Stain (Life technologies).

2.4. BCG-activation of Ag85A-specific CD4+ T cells

BCG Tokyo (a kind gift from Dr M. Behr, McGill University, Canada) was grown as described previously [10]. Prior experiments had indicated that transcription of potentially cytotoxic genes by antigen-specific stimulated CD4+ T-cells occurs at six days after stimulation. Therefore, CD4+ T-cells were stimulated as previously described [13] with small modifications; briefly, monocytes seeded in ice for 20–30 min and washed. For each animal.

2.5. Evaluation of mycobacterial growth inhibition

BCG has been established as an accepted microorganism for the evaluation of mycobacterial growth [11,12]. Prior to infection with BCG, Mφ were washed in antibiotic-free medium. 2 × 10^5 Mφ per ml were infected with BCG Tokyo in antibiotic-free medium at a BCG:Mφ ratio of 5:1 in 48-well plates (0.5 ml/well). After 16 h, wells containing BCG-infected Mφ were washed thrice with 0.5 ml HBSS (Gibco) and co-cultured for 24 h with BCG-activated CD4+ T cells, at a density of 8 × 10^5 cells/ml in a final volume of 0.5 ml of medium containing 50 μg/ml gentamicin; control wells contained infected Mφ but no CD4+ T cells. Supernatants were cryopreserved for analysis and cells were incubated with 0.55 ml/well HBSS (Gibco) and co-cultured for 24 h with BCG-activated CD4+ T-cells derived from three animals (two from one animal and one from each of the remaining animals). cDNA was synthesised from 100 ng total RNA using SuperScript VILO cDNA synthesis kits (Invitrogen) and a GeneAmp PCR System 9700 (Applied Biosystems) at 42 °C for 1 h and 85 °C for 5 min. Bovine perforin, granulysin, granzyme A and GAPDH gene transcription were determined using 2 μl of the cDNA template and 1 μl Taqman Gene expression Assay (20x) primer in a 20 μl Fast Advanced Mastermix Real-Time PCR reaction (Applied Biosystems, UK) using a Viia Real-time PCR System (2 min 50 °C hold, 20 sec 95 °C hold, 40 cycles of 1 sec 95 °C denature and 20 sec anneal/extend). Relative BCG-stimulated gene transcription was determined using the ΔΔCt method with GAPDH as the reference gene. Data shown are for day six relative to day zero. Taqman assay reference codes for bovine perforin, granulysin, granzyme A and GAPDH are provided in Table 1 (Thermo Fisher).

2.8. Statistics

Data analysis was performed using GraphPad Prism version 7 (GraphPad Software, La Jolla, CA, USA). Comparisons were made using the unpaired two-tailed t-test with significance level set at 5%.

3. Results

Ag85A-specific CD4+ T cell lines derived from BCG-vaccinated cattle, before and after boosting with Ad5-85A (generated and cryo-preserved in a previous study [7]), were evaluated for recognition of BCG-infected autologous Mφ in a 24 h co-culture system adapted from Endsley et al. [13]. Mycobacterial growth inhibition was assessed by determining the reduction of BCG load after co-culture (Fig. 2A). No difference in the ability to inhibit mycobacterial growth was found between Ag85A-specific CD4+ T cells lines obtained prior to and after boost, suggesting that boosting BCG-vaccinated cattle with Ad5-85A does not increase the anti-mycobacterial capacity of Ag85A-specific CD4+ T cells. Similarly, no statistically significant differences were found in the secretory profiles of the pro-inflammatory cytokines IL-1β, IL-12, IFN-γ and TNF-α (Fig. 2B–E) between cultures containing pre-boost and post-boost Ag85A-specific CD4+ T cells. Nevertheless, there were common trends towards lower amounts of pro-inflammatory cytokines in post-boost cultures. In contrast, we observed a statistically signif-

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Table 1

| Reactant        | Reference Code          |
|-----------------|-------------------------|
| Perforin        | B03816262_m1            |
| Granulysin      | B03287460_g1            |
| Granzyme        | B03271042_m1            |
| GAPDH           | B03210914_g1            |
significant increase in IL-10 secretion in the cultures containing Ag85A-specific CD4+ T cells obtained post-boost (Fig. 2F) compared to the IL-10 levels induced in Ag85A-specific CD4+ T cells obtained pre-boost.

The observed lack of difference in anti-mycobacterial capacity of Ag85A-specific CD4+ T cell lines ex vivo is consistent with comparable pre- and post-boost transcription of effector molecules thought to be involved in the killing of mycobacteria, (perforin, granulysin and granzyme A, [Fig. 3]).

4. Discussion

In this study, boosting BCG vaccinated cattle with Ad5-85A did not induce significant differences in Ag85A-specific CD4+ T cell lines obtained post-boost compared to cell lines obtained prior to boosting in terms of secretion of pro-inflammatory cytokines, transcription of molecules associated with cytotoxicity, or control of mycobacteria. However, Ag85A-specific CD4+ T cell lines obtained post-boost secreted more of the immune regulatory cytokine IL-10 than CD4+ T cell lines obtained prior to viral boosting.

It has been proposed that the induction of robust Th1 responses is a strategy employed by mycobacteria to facilitate its multiplication and dissemination [14–18]. More recently, Moguche et al. [19] showed in mice that continuous expression of ESAT-6 drives the expansion and maintenance of ESAT-6 specific T-cells. This continuous expansion resulted in large numbers of terminally differentiated ESAT-6 specific T-cells with limited protective capacity. In contrast, expression of Ag85 is limited to the early stages of infection, resulting in the priming of Ag85A/Ag85B specific memory T-cells which, although functional, are reduced in numbers due to the limited amount of Ag85A present during infection in later stages of infection.
It is likely that the level of protection observed in BCG vaccinated and Ad5–Ag85A boosted cattle was in part due to the expansion of the pool of cells specific for Ag85A [7]. This increase in the number of functionally active Ag85A-specific CD4+T-cells prior to infection enabled Ag85A to be detected early during infection, when Ag85A is more likely to be expressed by mycobacteria. Thus, we speculate that it is the availability of a greater number of Ag85A-specific CD4+ T-cells, induced by boosting (as previously shown [7]), which led to a greater control of mycobacteria (rather than any enhancement in anti-mycobacterial mechanisms which we did not detect). However, the control of mycobacteria by Ag85A-specific CD4+ T-cells appears to be accompanied by the production of IL-10; this is somewhat surprising as IL-10 has been associated with a decrease in protection against mycobacteria [20,21]. On the other hand IL-10 is an immune-regulatory/anti-inflammatory cytokine that contributes to the control of IFNγ responses which, whilst necessary for protection against mycobacteria, have been positively associated with pathology induced by M. bovis [22]. In this work the selection of CD4+ cells was based on their proliferative response, first in an unbiased manner by stimulation with PHA and then in an antigen specific manner by stimulation with Ag85A. It has been shown that cells detected in proliferative assays, such as the one used in this work, do not necessarily correlate with other types of assays such as those detecting production of IFNγ (Steinbach, S. al unpublished observation). Thus it is possible that protection induced by Ad5–Ag85A may be the result of the induction of two functionally different Ag85A-specific CD4+ T-cell populations: one population producing inflammatory cytokines, which were able to control, directly or indirectly, mycobacteria; and one population producing IL-10, with anti-inflammatory properties capable of controlling pathology. Successful vaccination against mycobacteria requires the control of the pathogen and of the detrimental immune response induced by the pathogen. The data obtained from these experiments contribute to our understanding of the nature of the immune response required for protection against tuberculosis in cattle. This information is required for the formulation of more rationally designed vaccines capable of inducing protective immune responses whilst avoiding the induction of pathogenic immune responses.

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Conflict of interests

None. Hannah J. Metcalfe adapted the CD4+ T cell methods to the experiments, performed the experiments and wrote the paper; Lucia Biffar contributed to the design and implementation of the MGIT analysis; Sabine Steinbach optimised the bovine CD4+T cell library/avidity methods and reviewed/editied the paper; Efraín Guzmán provided advice in the generation of monocyte derived macophages and macrophage staining; Tim Connelly was involved in design of the project and contributed to experimental planning; W. Ivan Morrison was involved in design of the project, contributed to experimental planning and reviewed/editied the paper; Bernardo Villarreal-Ramos and Martin Vordermeier were both involved in design of the project, contributed to experimental planning, provided advice in the setting up of the system and reviewed/editied the paper. All authors approved the final version of the submitted manuscript.

References

[1] Krebs JR, Anderson R, Clutton-Brock T, Morrison I, Young D, Donnelly C. Bovine tuberculosis in cattle and badgers – report to the Rt Hon Dr Jack Cunningham MP. The Ministry of Agriculture FaF; 1997.
[2] Defra. The strategy for achieving officially bovine tuberculosis free status for England. In: Defra, editor. England, UK: Defra; 2014.
[3] Welsh Government. Bovine TB eradication programme. Wales, UK: Welsh Government; 2017.
[4] Vordermeier HM, Villarreal-Ramos B, Cockle PJ, McAulay M, Rhodes SG, Thacker T, et al. Viral booster vaccines improve Mycobacterium bovis BCG-induced protection against bovine tuberculosis. Infect Immun 2009;77(8):3364–73.
[5] Dean G, Whelan A, Clifford D, Salguero FJ, Xing Z, Gilbert S, et al. Comparison of the immunogenicity and protection against bovine tuberculosis following immunization by BCG-priming and boosting with adenosine or protein based vaccines. Vaccine 2014;32(11):1304–10.
[6] Geiger R, Duhem T, Lanzavecchia A, Sallusto F. Human naive and memory CD4+ T cell repertoires specific for naturally processed antigens analyzed using libraries of amplified T cells. J Exp Med 2009;206(7):1525–34.
[7] Metcalfe HJ, Steinbach S, Jones GJ, Connelley T, Morrison WI, Vordermeier M, et al. Protection associated with a TB vaccine is linked to increased frequency of Ag85A-specific CD4+ T cells but no increase in avidity for Ag85A. Vaccine 2016;34(38):4520–5.
[8] Norimatsu M, Harris J, Chance V, Dougan G, Howard CJ, Villarreal-Ramos B. Differential response of bovine monocyte-derived macrophages and dendritic cells to infection with Salmonella typhimurium in a low-dose model in vitro. Immunology 2003;108(1):55–61.
[9] Helft J, Böttcher J, Chakravarty P, Zelenay S, Huotari J, Schraml BU, et al. GM-CSF mouse bone marrow cultures comprises a heterogeneous population of CD11c(-)/MHCII(+) macrophages and dendritic cells. Immunity 2015;42(5):1197–211.
[10] Villarreal-Ramos B, Berg S, Chamberlain L, McShane H, Hewinson RG, Clifford D, et al. Development of a BCG challenge model for the testing of vaccine candidates against tuberculosis in cattle. Vaccine 2014;32(43):5645–9.
[11] Cheon SH, Kampmann B, Hisre AG, Phillips M, Song HY, Landén K, et al. Bactericidal activity in whole blood as a potential surrogate marker of immunity after vaccination against tuberculosis. Clin Diagn Lab Immunol 2002;9(4):901–7.
[12] Fletcher HA, Tanner R, Walls RS, Meyer J, Manjaly ZR, Harris S, et al. Inhibition of mycobacterial growth in vitro following primary but not secondary vaccination with Mycobacterium bovis BCG. Clin Vaccine Immunol 2013;20(11):1683–9.
[13] Endsley JJ, Hogg A, Shell LJ, McAulay M, Coffey T, Howard C, et al. Mycobacterium bovis BCG vaccination induces memory CD4+ T cells characterized by effector biomarker expression and anti-mycobacterial activity. Vaccine 2007;25(50):8384–94.
[14] Coscolla M, Copin R, Sutherland J, Gehre F, de Jong B, Owolabi O, et al. Tuberculosis T cell epitope analysis reveals paucity of antigenic variation and identifies rare variable TB antigens. Cell Host Microbe 2015.
[15] Woodworth JS, Anderssen P. Reprogramming the T cell response to tuberculosis. Trends Immunol 2016;37(2):81–3.
[16] Orme IM, Robinson RT, Cooper AM. The balance between protective and pathogenic immune responses in the TB-infected lung. Nat Immunol 2015;16(1):57–63.
[17] Woodworth JS, Aagaard CS, Hansen PR, Cassidy JP, Agger EM, Andersen P. Protective CD4 T cells targeting cryptic epitopes of Mycobacterium tuberculosis resist infection-driven terminal differentiation. J Immunol 2014;192(7):3247–58.
[18] Andersen P, Woodworth JS. Tuberculosis vaccines–rethinking the current paradigm. Trends Immunol 2014;35(8):387–95.
[19] Moguche AO, Mussuvu M, Penn-Nicholson A, Plumlee CR, Mearns H, Goldenbays H, et al. Antigen availability shapes T cell differentiation and function during tuberculosis. Cell Host Microbe 2017;21(6):695–706 e5.
[20] Moreira-Texeira L, Redford PS, Stavropoulos E, Ghilardi N, Maynard CL, Weaver CT, et al. T cell-derived IL-10 impairs host resistance to Mycobacterium tuberculosis infection. J Immunol 2017;198(2):613–22.
[21] Redford PS, Boonstra A, Reid S, Pitt J, Graham C, Stavropoulos E, et al. Enhanced protection to Mycobacterium tuberculosis infection in IL-10 deficient mice is accompanied by early and enhanced Th1 responses in the lung. Eur J Immunol 2010;40(1):220–10.
[22] Vordermeier HM, Chambers MA, Cockle PJ, Whelan AO, Simmons J, Hewinson RG. Correlation of ESAT-6-specific gamma interferon production with pathology in cattle following mycobacterium bovis BCG vaccination against experimental bovine tuberculosis. Infect Immun 2002;70(6):3026–32.