OPEN ACCESS

ORIGINAL ARTICLE

Developing in vitro expanded CD45RA$^+$ regulatory T cells as an adoptive cell therapy for Crohn's disease

James B Canavan,[1,2,3,4] Cristiano Scottà,[1,3,5] Anna Vossenkämper,[6] Rimma Goldberg,[1,2,3,4] Matthew J Elder,[1,2,3] Irit Shoval,[7] Ellen Marks,[1,2,3] Emilie Stolarczyk,[3,8] Jonathan W Lo,[1,2,3] Nick Powell,[1,2,3,4] Henrieta Fazekasova,[1,3,5] Peter M Irving,[4] Jeremy D Sanderson,[4] Jane K Howard,[3,8] Simcha Yagel,[9] Behdad Afzali,[1,3,5] Thomas T MacDonald,[6] Maria P Hernandez-Fuentes,[1,2,3] Nahum Y Shpigel,[7] Giovanna Lombardi,[1,3,5] Graham M Lord[1,2,3]

▶ Additional material is published online only. To view please visit the journal online (http://dx.doi.org/10.1136/gutjnl-2014-306919).

For numbered affiliations see end of article.

Correspondence to
Professor Graham Lord, Department of Experimental Immunobiology, King's College London, 5th Floor, Tower Wing, Guy's Hospital, London SE1 9RT, UK; graham.lord@kcl.ac.uk

JBC and CS contributed equally.

Received 3 February 2014
Revised 1 December 2014
Accepted 23 December 2014
Published Online First
24 February 2015

ABSTRACT

Background and aim Thymus-derived regulatory T cells (T_{regs}) mediate dominant peripheral tolerance and treat experimental colitis. T_{regs} can be expanded from patient blood and were safely used in recent phase 1 studies in graft versus host disease and type 1 diabetes. T_{reg} cell therapy is also conceptually attractive for Crohn's disease (CD). However, barriers exist to this approach. The stability of T_{regs} expanded from Crohn's blood is unknown. The potential for adoptively transferred T_{regs} to express interleukin-17 and exacerbate Crohn's lesions is of concern. Mucosal T cells are resistant to T_{reg}-mediated suppression in active CD. The capacity for expanded T_{regs} to home to gut and lymphoid tissue is unknown.

Methods To define the optimum population for T_{reg} cell therapy in CD, CD4$^+$CD25$^+$CD127^{lo}CD45RA$^+$ and CD4$^+$CD25$^+$CD127^{lo}CD45RA$^-$ T_{reg} subsets were isolated from patients' blood and expanded in vitro using a workflow that can be readily transferred to a good manufacturing practice background.

Results T_{regs} can be expanded from the blood of patients with CD to potential target dose within 22–24 days. Expanded CD45RA$^+$ T_{regs} have an epigenetically stable *FOXP3* locus and do not convert to a Th17 phenotype in vitro, in contrast to CD45RA$^-$ T_{regs}. CD45RA$^+$ T_{regs} highly express $\alpha_4\beta_7$ integrin, CD62L and CC motif receptor 7 (CCR7). CD45RA$^+$ T_{regs} also home to human small bowel in a C.B-17 severe combined immune deficiency (SCID) xenotransplant model. Importantly, in vitro expansion enhances the suppressive ability of CD45RA$^+$ T_{regs}. These cells also suppress activation of lamina propria and mesenteric lymph node lymphocytes isolated from inflamed Crohn's mucosa.

Conclusions CD4$^+$CD25$^+$CD127^{lo}CD45RA$^+$ T_{regs} may be the most appropriate population from which to expand T_{regs} for autologous T_{reg} therapy for CD, paving the way for future clinical trials.

Significance of this study

What is already known on this subject?

- Thymically derived regulatory T cells (T_{regs}) can modulate effector immune responses and, when expanded in vitro, have recently shown promise for graft versus host disease and type 1 diabetes in humans, leading to interest in this therapeutic approach for Crohn's disease.
- Barriers to autologous T_{reg} therapy in Crohn's include the requirement for in vitro expansion to a target dose, potential T_{reg} plasticity to pathogenic interleukin-17$^+$ cells, uncertain homing to mucosal tissue and effector T cell resistance to T_{reg}-mediated suppression in inflamed Crohn's mucosa.
- Initial enrichment on the basis of CD45RA$^+$ expression can improve the phenotypic stability of an expanded T_{reg} population obtained from healthy control blood, but the value of this approach in Crohn's disease is unknown.

What are the new findings?

- We show that it is technically feasible to expand functional T_{regs} to numbers consistent with a target dose from the blood of patients with Crohn's disease.
- In vitro expansion enhances the in vitro suppressive activity of these cells. Expanded T_{regs} suppress activation of lamina propria and mesenteric lymph node lymphocytes isolated from inflamed Crohn's mucosa.
- In contrast to T_{regs} expanded from CD45RA$^-$ precursors, expanded CD45RA$^+$ T_{regs} have epigenetically stable FOXP3 expression and are resistant to Th17 conversion.
- Expanded CD45RA$^+$ T_{regs} also express $\alpha_4\beta_7$ integrin, CD62L and CCR7, and home to human small bowel in a SCID mouse bearing subcutaneously implanted human intestine.

INTRODUCTION

Thymically derived FOXP3$^+$ regulatory T cells (T_{regs}) are key mediators of peripheral tolerance and are likely to have a role in preventing inappropriate mucosal inflammation in response to bacterial, and other, luminal antigens. In mice, T_{reg} depletion impairs oral tolerance.[1] Adoptively transferred T_{regs} prevent the onset of colitis or treat established colitis in a number of murine models.[2–7]

To cite: Canavan JB, Scottà C, Vossenkämper A, *et al*. *Gut* 2016;**65**:584–594.

Significance of this study

How might it impact on clinical practice in the foreseeable future?

- These results demonstrate that initial T_{reg} enrichment on the basis of CD45RA$^+$ expression is required to produce a phenotypically stable and suppressive T_{reg} population following in vitro expansion and that these in vitro expanded cells have the capacity to home to mucosal tissue, paving the way for autologous T_{reg} therapy in this therapeutically challenging disease.

FOXP3 mutations lead to multisystem autoimmunity with enteropathy in mice and humans.[8 9] Disruption of other key molecules implicated in T_{reg} function, such as transforming growth factor (TGF)-β, Cytotoxic T Lymphocyte-Associated (CTLA)-4, interleukin (IL)-10R subunits, IL-2 or its receptor subunits, is associated with autoimmunity and intestinal inflammation.[10]

Human peripheral blood (PB) or umbilical cord blood T_{regs} can be expanded in vitro through T cell receptor (TCR) stimulation in the presence of IL-2.[11–26] In vitro expanded human T_{regs} prevent transplant rejection,[27 28] transplant arteriosclerosis[29] and graft versus host disease (GvHD)[21 30] in humanised mice. Promisingly, recent phase 1 clinical trials have shown T_{reg} cell therapy to be safe in patients with GvHD[12 24] and type 1 diabetes.[18] Additional phase 1 studies have started in renal (the ONE study) and liver transplantation (ThRIL study).[19 31]

Lamina propria (LP) T_{regs} are increased in the mucosa of patients with active Crohn's disease (CD) and decreased in blood, compared with healthy controls.[32–34] LP T_{regs} obtained from inflamed CD mucosa suppress proliferation of conventional CD4$^+$CD25$^{lo/int}$ T cells (T_{con}) obtained from blood but not LP T_{cons},[35] suggesting that mucosal T_{cons} in active CD may be resistant to T_{reg}-mediated suppression. LP T_{cons} from CD mucosa overexpress Smad7, an inhibitor of TGF-β signalling, which confers resistance to T_{reg}-mediated suppression.[35 36] Activated T_{cons} also have an effector-memory phenotype, conferring relative resistance to T_{reg}-mediated suppression.[37] However, T_{regs} expanded in vitro in the presence of rapamycin from the PB of patients with end-stage renal failure (ESRF), systemic lupus erythematosus (SLE), rheumatoid arthritis (RA), multiple sclerosis (MS) and asthma are more suppressive than freshly isolated T_{regs} obtained from the same donor.[26 38] If it can be shown that in vitro expansion enhances the suppressive ability of CD PB T_{regs} and that these expanded cells suppress mucosal inflammation, parenteral therapy with autologous in vitro expanded T_{regs} generated from CD PB would become a conceptually attractive approach to induce remission in active CD.

IL-17 contributes to mucosal homoeostasis but has also been implicated in the pathogenesis of CD. T_{regs} isolated from healthy donor PB or tonsils can be induced to express IL-17 and the Th17 transcription factor RORC when activated in vitro in the presence of IL-1, IL-2, IL-21 and IL-23.[39–42] Although major sources of IL-17 in the gut include T_{cons} and γδ T cells, a proportion of T_{regs} obtained from inflamed CD mucosa co-express FOXP3 and IL-17.[43] Th1 T_{reg} plasticity has also been described in vitro and in vivo.[44 45] In humans, phenotypically distinct T_{reg} populations can be delineated on the basis of CD45RA expression.[17 46] 'Resting' CD4$^+$CD25^{hi}CD127^{lo}CD45RA$^+$ T_{regs} (rT_{regs}) are resistant to induction of IL-17 and interferon (IFN)-γ in vitro.[46] In contrast, 'activated' CD4$^+$CD25^{hi}CD127^{lo}CD45RA$^-$ T_{regs} (aT_{regs}) can be induced to express IL-17 and IFN-γ in vitro.[46] Similarly, T_{regs} expanded from healthy donor CD45RA$^+$ T_{regs} (in the absence of rapamycin) do not contain cytokine producers and are highly suppressive, while T_{regs} expanded from CD45RA$^-$ T_{regs} express proinflammatory cytokines and lose *FOXP3* expression with repetitive stimulation in vitro.[17 47] T_{regs} expanded from healthy control CD45RA$^-$ precursors (but not CD45RA$^+$ precursors) also have stimulation-induced demethylation of *RORC*, which may be permissive for IL-17 expression.[48] Furthermore, imprinting $\alpha_4\beta_7$ integrin expression on in vitro expanded T_{regs} by supplementing culture with all-trans retinoic acid (ATRA) results in high IL-17 expression.[21] Even though IL-17$^+$ T_{regs} isolated from human blood and tonsil retain their suppressive ability in vitro,[39–41] the potential for adoptively transferred T_{regs} to exacerbate inflammation in CD lesions through the production of proinflammatory cytokines is of significant concern.

Using cell enrichment strategies achievable with currently available good manufacturing practice (GMP) technologies, we show that initial enrichment on the basis of CD45RA$^+$ expression is required to generate a homogenous and epigenetically stable T_{reg} population following expansion, in the presence of rapamycin, from the PB of patients with CD. These cells are resistant to Th17 plasticity, express lymphoid and gut homing markers, and home to human gut following adoptive transfer to a SCID mouse bearing subcutaneously implanted human small bowel (SB). In vitro expansion also enhances the suppressive ability of these cells, licensing them to suppress activation of LP and mesenteric lymph node (MLN) T_{cons} obtained from inflamed CD resection specimens. These data suggest that CD PB CD4$^+$CD25^{hi}CD127^{lo}CD45RA$^+$ cells may be the most appropriate population from which to expand T_{regs} in vitro for forthcoming clinical trials of autologous T_{reg} cell therapy in CD.

MATERIALS AND METHODS

Patient samples

Following Institutional Review Board (IRB) approval (SE London REC 2; 10/H0804/65 and East London REC 2 (10/H0704/74)), patients with CD attending Guy's & St Thomas' National Health Service (NHS) Foundation Trust and Bart's Health NHS Trust were invited to donate blood and/or resected tissue. Prospective written consent was obtained. Demographic details are shown in table 1.

T_{reg} enrichment and sorting

Online supplementary figure S1 illustrates the experimental design. Peripheral blood mononuclear cells (PBMCs) were isolated by density gradient centrifugation over lymphocyte separation medium (LSM) 1077 and CD4$^+$ lymphocytes enriched to >95% by positive magnetic activated cell separation (MACS) selection (Miltenyi, Bergisch-Gladbach, Germany). Lymphocytes were labelled using the 'Human Regulatory T Cell Sorting Kit' (BD Biosciences, San Diego, California, USA), as described previously,[25] and sorted to CD4$^+$CD25^{hi}CD127^{lo}CD45RA$^+$ and CD4$^+$CD25^{hi}CD127^{lo}CD45RA$^-$ T_{reg} subsets, and autologous CD4$^+$CD25$^-$ T_{cons} on a FACSAria (BD; see online supplementary figure S2A–D). Median (IQR) postsort purity was 86.5% (80.8–91.6%; n=13) for CD4$^+$CD25^{hi}CD127^{lo}CD45RA$^+$ T_{regs} (CD45RA$^+$ T_{regs}) and 92.7% (87.7–94.9%; n=13) for CD4$^+$CD25^{hi}CD127^{lo}CD45RA$^-$ T_{regs} (CD45RA$^-$ T_{regs}). Autologous T_{cons} were stored at −80°C.

Table 1 Demographic details of study patients

Female sex	6	(46.1%)
Age (mean±SD)	42.6	(±13.0)
Disease duration	15.4	(±10.4)
Age at diagnosis (mean±SD)	27.7	(±13.1)
Diagnosis <16 years old (A1)	2	(15.4%)
Diagnosis 17–40 years old (A2)	9	(69.2%)
Diagnosis >40 years old (A3)	2	(15.4%)
Location		
Ileal only (L1)	1	(7.7%)
Colonic only (L2)	4	(30.8%)
Ileo-colonic (L3)	8	(61.5%)
Concomitant upper GI disease (L4)	2	(15.4%)
Perianal disease (p)	2	(15.4%)
Behaviour		
Inflammatory (B1)	9	(69.2%)
Stricturing (B2)	2	(15.4%)
Penetrating (B3)	2	(15.4%)
HBI (median, range)	0	(0–7)
Active disease HBI ≥5	4	(30.8%)
Previous surgery	8	(61.5%)
Medications		
Thiopurines	7	(53.8%)
Biologics	4	(30.8%)
Others	3	(23.1%)

GI, gastrointestinal; HBI, Harvey Bradshaw Index.

In vitro generation of T_{reg} lines

Precursor T_{reg} populations were expanded in vitro as described previously[21 25] and described in detail in online supplemental methods.

Cell surface and intracellular stains

Fluorochrome-conjugated antibodies, buffers and experimental technique are listed in online supplemental methods.

Assessment of the in vitro suppressive ability of putative T_{regs}

Assays to determine T_{reg} function in vitro were performed as described previously,[25 49] and described in detail in the online supplemental methods.

rtPCR

Following total RNA extraction from Trisure (Bioline, London, UK), cDNA was synthesised using the RevertAid First Strand cDNA Synthesis Kit and multiplex rtPCR performed in duplicate using the Maxima Probe/ROX qPCR Master Mix (both Thermo Fischer Scientific) on a BioRad C1000 Thermal Cycler. Primers are listed in online supplemental methods.

Estimation of cytokine concentrations

Cytokine concentrations were estimated in culture supernatants using the Cytometric Bead Array (CBA) Human Th1/Th2/Th17 Cytokine Kit (BD) or sandwich ELISAs (R&D), as indicated.

Assessment of IL-17 production under proinflammatory conditions

In vitro generated T_{regs} were activated with anti-CD3/anti-CD28 beads at a 1:1 ratio and cultured at 10^6 cells/mL in complete Roswell Park Memorial Institute (RPMI) for 5 days at 37°C/5% CO_2, supplemented with the following cytokine cocktails, as previously described:[21 23 39] (A) IL-2 (10 IU/mL, Proleukin); (B) IL-2, IL-1 (10 ng/mL), IL-6 (4 ng/mL) and TGF-β (5 ng/mL); (C) IL-2, IL-21 (25 ng/mL), IL-23 (25 ng/mL) and TGF-β (all R&D Systems). Supernatant IL-17 concentrations were measured by ELISA.

Assessment of FOXP3 promoter demethylation

Genomic DNA was isolated using a 'DNeasy kit' (Qiagen, Manchester, UK). Bisulfite conversion and assessment of the methylation status of the *FOXP3* T_{reg}-specific demethylated region (TSDR) was performed by Epiontis.[50 51] The genomic locations of *FOXP3* and *GAPDH* CpG-rich regions probed have been reported.[51]

Isolation of LP mononuclear cells and MLN mononuclear cells

LP mononuclear cells (LPMCs) and MLN mononuclear cells (MLNMCs) were isolated as described previously[52] and listed in online supplemental methods.

C.B-17 SCID mouse human intestinal xenotransplant model

Experimental design is illustrated in figure 3C. The C.B-17 SCID mouse human intestinal xenotransplant model has been described previously[53 54] and is described in detail in online supplemental methods. IRB and IACUC approvals were obtained prospectively (Ethics Committee for Animal Experimentation, Hebrew University of Jerusalem; MD-11-12692-4 and the Helsinki Committee of the Hadassah University Hospital; 81-23/04/04). Techniques for the detection of adoptively transferred T_{regs} are also described in detail in online supplemental methods.

Statistical analysis

Statistical analysis was carried out using GraphPad Prism 5 (GraphPad Software Inc, La Jolla, California, USA) and the methods used are described in detail in the online supplemental methods.

RESULTS

T_{regs} can be expanded from the blood of patient with CD using GMP-compatible protocols

Hoffmann *et al*[17] showed that initial T_{reg} enrichment on the basis of $CD45RA^+$ expression was required to expand homogenous and stable T_{reg} lines from healthy donors in the absence of supplemental rapamycin. Rapamycin prevents the outgrowth of contaminating T_{cons} in T_{reg} cultures, and may make the requirements for the starting population less stringent.[11 13 15 21 23 55] However, the optimum precursor population from which to expand a homogenous, suppressive and epigenetically stable T_{reg} population from CD PB is currently unknown. In previous studies, we accomplished in vitro expansion of in vitro suppressive T_{regs} from healthy controls[21] and renal transplant candidates.[26] We sought to determine if T_{regs} could be expanded in vitro from the blood of patients with CD.

Freshly isolated $CD4^+$ lymphocytes from 13 patients with CD were fluorescence-activated cell sorting (FACS)-sorted into $CD4^+CD25^{hi}CD127^{lo}CD45RA^+$ (median (IQR) of 2200 cells/mL PB (860–4400)) and $CD4^+CD25^{hi}CD127^{lo}CD45RA^-$ subsets (3700 cells/mL (2000–4500)), then expanded in vitro in the presence of high-dose IL-2, rapamycin and anti-CD3/anti-CD28 beads. Active disease, evidenced by a Harvey Bradshaw Index >5 (n=4) *or* elevated C reactive protein (n=1), was not associated with a significantly reduced yield (see online supplementary figure S2E). Donor clinical characteristics are given in table 1.

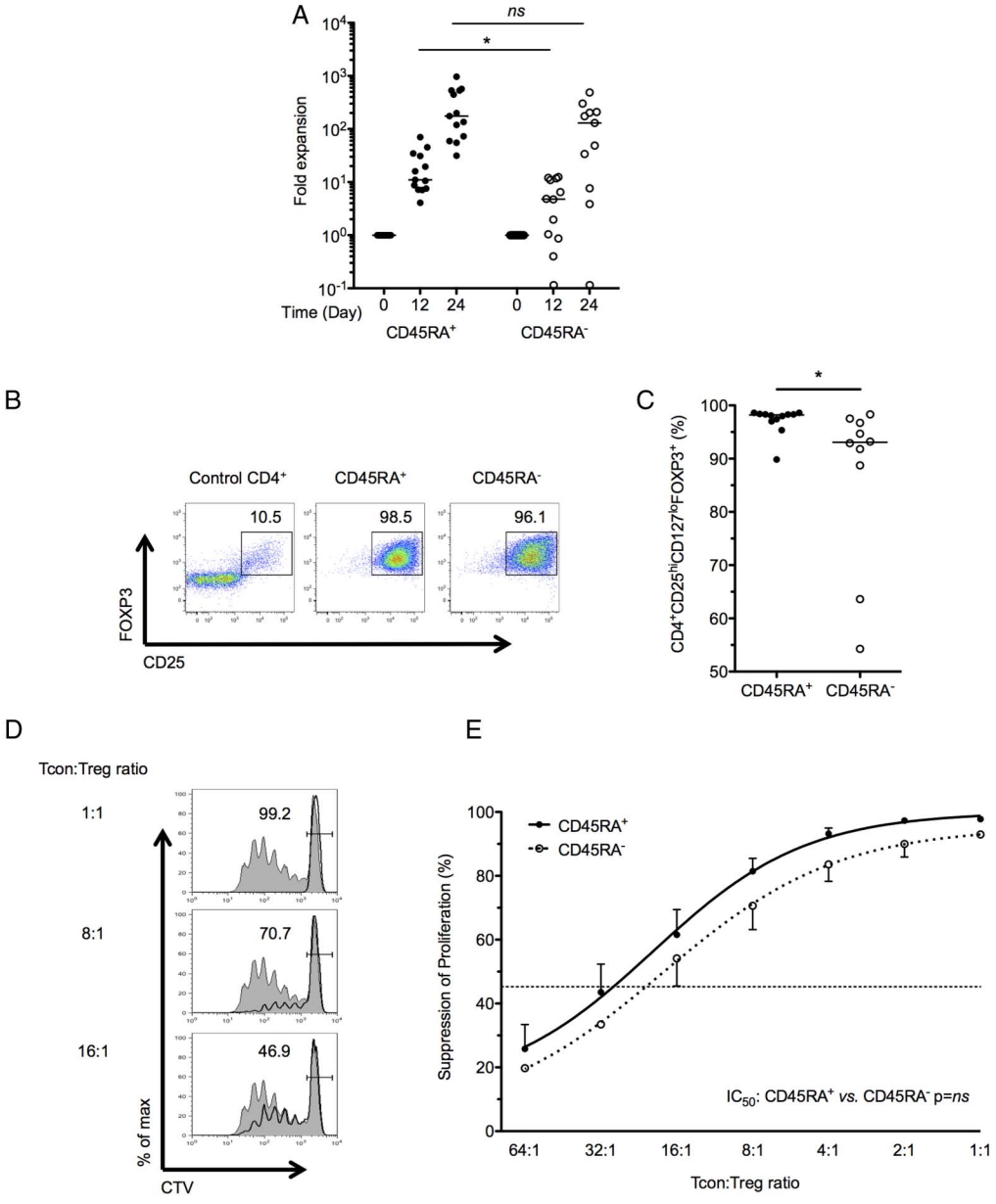

Figure 1 Expansion, phenotype and potency of in vitro expanded T_{regs}. (A) Cumulative fold expansion of T_{reg} lines at days 12 and 24 of culture, grouped according to $CD4^+CD25^{hi}CD127^{lo}CD45RA^+$ or $CD4^+CD25^{hi}CD127^{lo}CD45RA^-$ precursors; n=13 each, bar: median. (B) Representative FACS plots gated on live events showing CD25 and FOXP3 expression at D24. (C) Proportion of T_{regs} with a $CD4^+CD25^{hi}CD127^{lo}$ T_{reg} phenotype at D24. (D) Representative plots from a proliferation assay, illustrating dose-dependent suppression of T_{con} proliferation by $CD45RA^+$ T_{regs}. Proliferation CTV-labelled autologous $CD4^+CD25^-$ T_{cons} alone (filled) or with T_{regs} at various T_{con}:T_{reg} ratios (bold line) is shown. (E) D24 T_{reg}-mediated suppression of T_{con} proliferation. Cumulative data showing mean±SEM suppression seen at each T_{con}:T_{reg} ratio. Pooled data from 29 T_{reg} lines. Comparisons between suppression seen in study conditions and mean non-specific suppression seen in '2X' control condition (dotted line) are shown. *p<0.05,***p<0.001 and ****p<0.0001. T_{regs}, thymus-derived regulatory T cells; FACS, fluorescence-activated cell sorting; T_{cons}, conventional $CD4^+CD25^{lo/int}$ T cells; CTV, Cell Trace Violet; NS, not significant.

Every $CD45RA^+$ T_{reg} line proliferated, to a median (IQR) of 175-fold (66–531; n=13) at D24 (figure 1A). In contrast, 3 of 13 (23%) $CD45RA^-$ T_{reg} lines did not proliferate and were discontinued. $CD45RA^-$ T_{regs} expanded 130-fold (8–209; n=10). Expanded T_{regs} were exclusively $CD4^+$ lymphocytes. Expression of CD25 and FOXP3 was comparable in D24 $CD45RA^+$ and $CD45RA^-$ T_{regs} (figure 1B), but a greater proportion of $CD45RA^+$ T_{regs} maintained a $CD4^+CD25^{hi}CD127^{lo}FOXP3^+$ phenotype (p=0.037; figure 1C).

Proliferation assays were performed to determine if in vitro expanded T_{regs} retained the ability to suppress proliferation of autologous $CD4^+CD25^-$ T_{cons}. $CD45RA^+$ and $CD45RA^-$ T_{regs} suppressed T_{con} proliferation to an equivalent degree (figure 1D–E), demonstrating specific suppression (vs the 2X cell density control) above an 8:1 T_{con}:T_{reg} ratio. $CD45RA^+$ and $CD45RA^-$ T_{regs} reduced IL-2 expression in 96 h co-culture supernatants (see online supplementary figure S3A). $CD45RA^+$ T_{regs} also suppressed IFN-γ expression in 96 h co-culture supernatants (see online supplementary figure S3B).

In vitro expanded $CD45RA^+$ T_{regs} are resistant to IL-17 induction and stably express FOXP3

The 'inflammatory potential' of in vitro expanded T_{regs} from patients with CD was examined. Genes important in

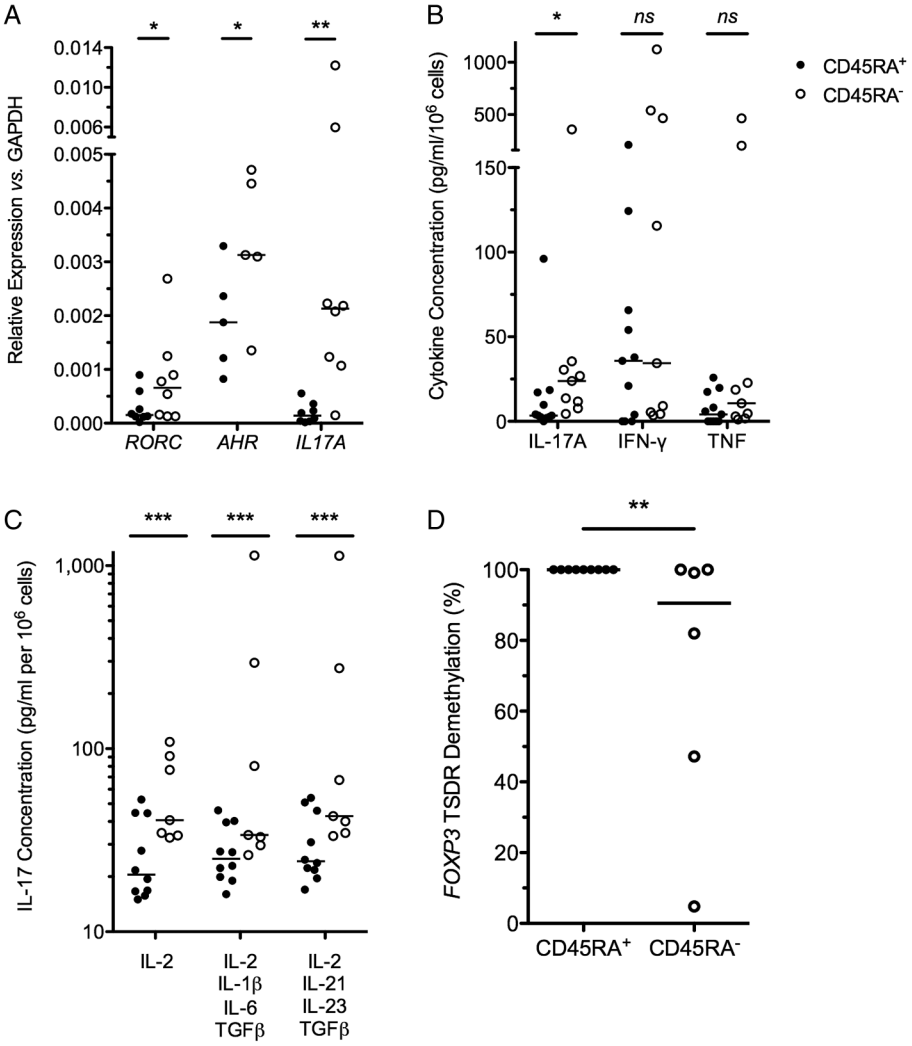

Figure 2 D24 CD45RA$^+$ T_{regs} are resistant to IL-17 induction. (A) Relative expression of *IL17A*, *RORC* and *AHR* in D24 CD45RA$^+$ and CD45RA$^-$ T_{regs}, relative to *GAPDH*; n=16, bar at median. (B) D24 T_{reg} IL-17, IFN-γ and TNF secretion in 24 h culture supernatants; n=20, bar at median. (C) IL-17 detected by ELISA from 5-day culture supernatants of D24 T_{regs} cultured in the absence of rapamycin but with supplemental IL-2 alone, a cocktail of IL-2, IL-1, IL-6 and TGF-β or a cocktail of IL-2, IL-21, IL-23 and TGF-β. n=17, bar at median. (D) % FOXP3 TSDR demethylation; n=15, bar at median. *p<0.05,**p<0.01, ***p<0.001. T_{regs}, thymus-derived regulatory T cells; IL, interleukin; IFN, interferon; TNF, tumour necrosis factor; TGF, transforming growth factor; TSDR, T_{reg}-specific demethylated region; NS, not significant.

Th17 biology, including *RORC*, *AHR* and *IL-17*, were significantly overexpressed in CD45RA$^-$ T_{regs}, in comparison with expression in paired CD45RA$^+$ T_{regs} (p<0.05 for each comparison, figure 2A). IL-17 secretion was also significantly different in these T_{reg} subsets. IL-17 expression was below the limit of detection in 10/11 (91%) CD45RA$^+$ T_{regs} and significantly higher in CD45RA$^-$ T_{regs} (p=0.02; figure 2B).

The potential of in vitro expanded T_{regs} to turn on an inflammatory programme following exposure to Th17-inducing cytokines, as occurs in vitro in T_{regs} isolated from blood,[39–41] was examined. D24 T_{regs} were washed and cultured for a further 5 days in the presence of IL-2 alone, or Th17-inducing cytokines (IL-2, IL-1, IL-6 and TGF-β or IL-2, IL-21, IL-23 and TGF-β; figure 2C). These proinflammatory cytokines failed to induce IL-17 production by CD45RA$^+$ T_{regs}. In contrast, IL-17 production by CD45RA$^-$ T_{regs} was 3-fold higher than CD45RA$^+$ T_{regs} in neutral conditions (IL-2 alone) and 10-fold higher in skewing conditions (p<0.001 each comparison).

To ensure that phenotypic stability of CD45RA$^+$ T_{regs} correlated with an epigenetically stable *FOXP3* locus, we determined the methylation status of the *FOXP3* 'TSDR' (figure 2D). We found the TSDR to be completely demethylated in all CD45RA$^+$ T_{reg} lines tested (100%; n=9), suggesting an epigenetically stable FOXP3 locus in CD45RA$^+$ T_{regs} even after 24d of in vitro expansion. In contrast, variable degrees of TSDR demethylation were seen in CD45RA$^-$ T_{reg} lines (median (IQR) of 90.6% (36.6%–100%); n=6; p=0.008).

In vitro expanded CD45RA$^+$ T_{regs} express homing receptors for gut and lymphoid tissue

The ability of in vitro expanded T_{regs} to home to relevant immune niches, where they may suppress inflammation, is thought to be critical for cell therapy. Consequently, the expression of gut homing receptors on in vitro expanded T_{regs} was examined by FACS (figure 3A, B). We found that D24 CD45RA$^+$ T_{regs} modestly expressed $\alpha_4\beta_7$ integrin and CCR6 (20.8%±7.8% and 12.2%±7.9%, respectively) and did not express CCR9. Both CD62L (84.8%±20.6%; p=0.04 vs CD45RA$^-$) and CCR7 (92.1%±12.8%; p=0.03) required for lymph node homing were more highly expressed in CD45RA$^+$ T_{regs} than CD45RA$^-$ T_{regs}. CCR4 (95.4%±4.2%) was also highly expressed.

Adoptively transferred CD45RA$^+$ T_{regs} home to inflamed human small intestine in a C.B-17 SCID human SB xenotransplant model

In view of the favourable phenotype of CD45RA$^+$ T_{regs} as a candidate cell therapy, we next sought to determine whether these cells could home to inflamed human SB in vivo. D24 CD45RA$^+$ T_{regs} were administered to a C.B-17 SCID mouse bearing human small intestinal xenotransplants and homing assessed

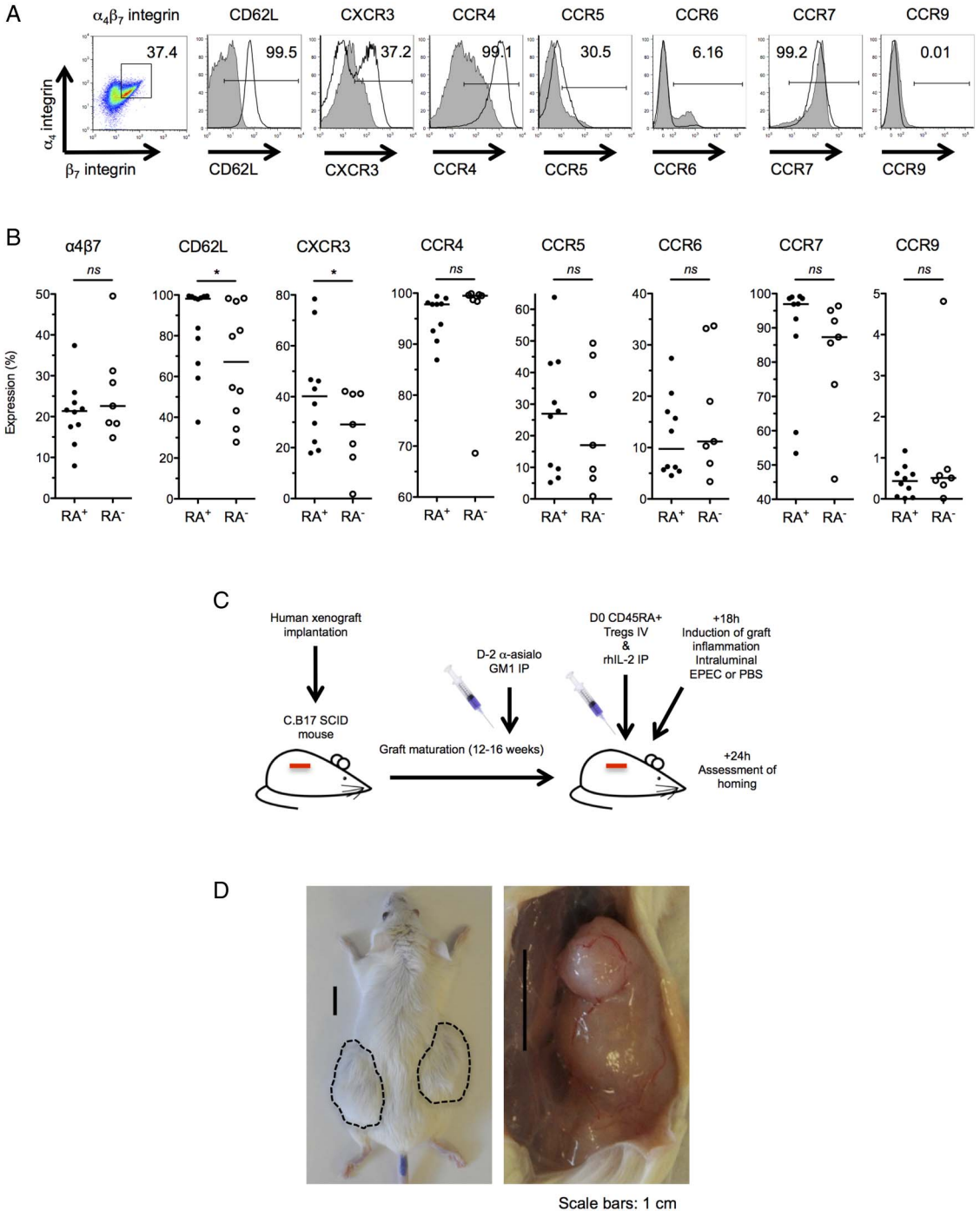

Figure 3 D24 CD45RA$^+$ T_{regs} express gut and lymphoid homing receptors and home to inflamed human LP in a C.B-17 severe combined immunodeficiency (SCID) mouse human intestinal XG model. (A) Representative FACS plots illustrating gut and lymphoid homing receptor expression on D24 CD45RA$^+$ T_{regs} (bold line). Gates were drawn on the basis of fully stained CD4$^+$ lymphocytes (filled) and fluorochrome minus one (FMO) controls. (B) Dot plots showing expression of intestinal and lymphoid homing receptors in D24 CD45RA$^+$ and CD45RA$^-$ T_{regs}. n=17; *p<0.05. (C) Design of the XG mouse experiment. (D) Left panel: mature XGs (circled) are visible subcutaneously on the dorsum of the mouse. Right panel: dorsal skin has been removed in an anaesthetised mouse to reveal the mucus-filled XG in situ (right panel). Microscopic images of the XG are shown in online supplementary figure S4A. (E) FACS plots showing live human CD45$^+$CD3$^+$CD4$^+$ events in single cell suspensions prepared from murine spleen, non-inflamed and inflamed XGs, 24 h after intravenous phosphate buffered saline (PBS) (left panels) or adoptive transfer of T_{regs} (right panels). The absolute numbers of CD3$^+$CD4$^+$ events in the XG human CD45$^+$ gates are highlighted. The gating strategy is illustrated in online supplementary figure S4B. (F) Immunofluorescence staining of XG cryosections with antihuman CD3 (red), antihuman CD45 (green) and 4′,6-diamidino-2-phenylindole (DAPI) (blue). (E and F) Representative of two independent experiments. T_{regs}, thymus-derived regulatory T cells; LP, lamina propria; XG, xenograft; FACS, fluorescence-activated cell sorting; EPEC, enteropathogenic *Escherichia coli*; NS, not significant.

24 h later (figure 3C, D). Intraluminal injection with enteropathogenic *Escherichia coli* was used to induce mucosal inflammation (see online supplementary figure S4A). Following adoptive transfer, human CD45$^+$CD3$^+$CD4$^+$ cells were detected in mouse spleen and inflamed human SB LP by FACS (see figure 3E; gating strategy online supplementary figure S4B),

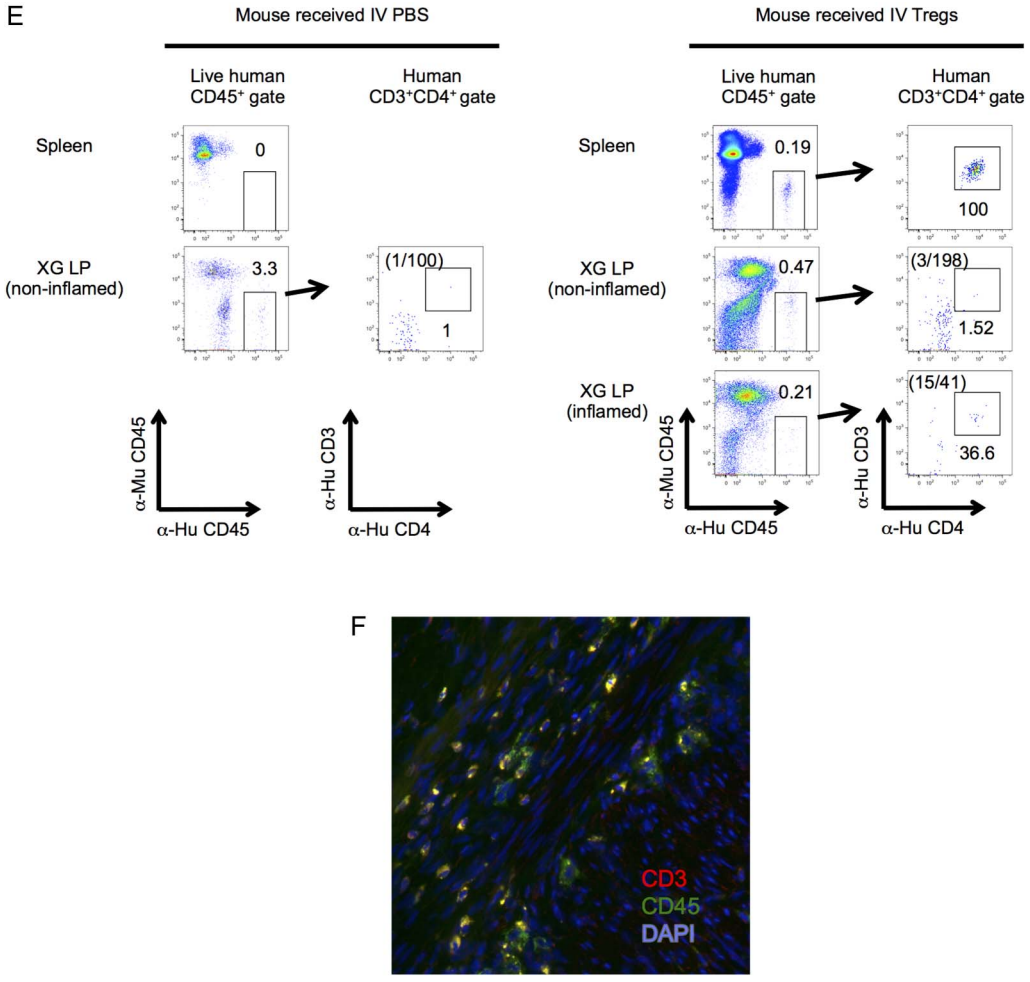

Figure 3 Continued

indicating that adoptively transferred CD45RA$^+$ T_{regs} homed to inflamed human SB LP in this model. This was confirmed by the detection of human CD45$^+$CD3$^+$ cells in inflamed human SB LP by immunofluorescence (figure 3F). We previously showed that human fetal SB contains a population of CD3$^-$CD7$^+$ cells that persist following xenotransplantation.[53] Human CD45$^+$CD3$^-$ events were also detected in non-inflamed human SB LP in both mice that received intravenous PBS and intravenous T_{regs} (figure 3E), suggesting that a population of long-lived human immune cells was co-transferred with the human SB transplant.

In vitro expansion enhances the in vitro suppressive ability of CD45RA$^+$ T_{regs}

LP T_{cons} from inflamed CD mucosa are resistant to in vitro suppression by autologous LP T_{regs}.[35 36] Consequently, it is possible that in vitro expanded T_{regs} will need an enhanced suppressive function in order to be successful as a future cell-based therapy. Expansion with supplemental rapamycin enhances the in vitro suppressive ability of T_{regs} from patients with ESRF, SLE, RA, MS and asthma.[26 38] In order to determine if in vitro expansion enhanced T_{reg} function in patients with CD, freshly isolated CD4$^+$CD25^{hi}CD127^{lo}CD45RA$^+$ T_{regs} or D24 CD45RA$^+$ T_{regs} that were expanded in vitro from these FACS-sorted CD4$^+$CD25^{hi}CD127^{lo}CD45RA$^+$ precursors were co-cultured with allogeneic Carboxyfluorescein succinimidyl ester (CFSE)-labelled CD4$^+$CD25$^-$ T_{cons} (n=3 independent experiments; cells from the same lot of single-donor, freeze-thawed T_{cons} for each experiment). D24 CD45RA$^+$ T_{regs} suppressed T_{con} proliferation to a greater degree than the freshly isolated CD4$^+$CD25^{hi}CD127^{lo}CD45RA$^+$ T_{regs} from which they were expanded, at both a 4:1 and 8:1 T_{con}:T_{reg} ratio ($p<0.01$ and $p<0.001$, respectively; figure 4A). This suggests that in vitro expansion enhances the suppressive ability of D24 CD45RA$^+$ T_{regs}.

In vitro expanded CD45RA$^+$ T_{regs} suppress proliferation and activation of MLN and LP T cells in active CD

We next wished to determine if D24 CD45RA$^+$ T_{regs} could suppress activation and proliferation of T_{cons} taken from the MLN and LP of patients with CD (figure 4B, C). MLNMCs were co-cultured with T_{regs} and CD3$^+$ proliferation assessed at 96 h. Dose-dependent T_{reg}-mediated suppression of MLN CD3$^+$ proliferation was seen at each MLNMC:T_{reg} ratio (figure 4D). We were unable to demonstrate in vitro suppression of LPMC CD3$^+$ proliferation with this technique, as both freshly isolated and freeze-thawed LPMCs obtained from inflamed CD mucosa died prior to acquisition at 96 h (n=4 independent experiments; see online supplementary figures S5 and S6).

We recently validated a novel co-culture assay for the assessment of in vitro expanded T_{reg} function. This takes advantage of T_{reg}-mediated suppression of the early activation marker CD154 (CD40 L) on T_{cons} at 7 h, which correlates with T_{reg}-mediated suppression of CFSE dilution and cytokine expression in T_{cons}

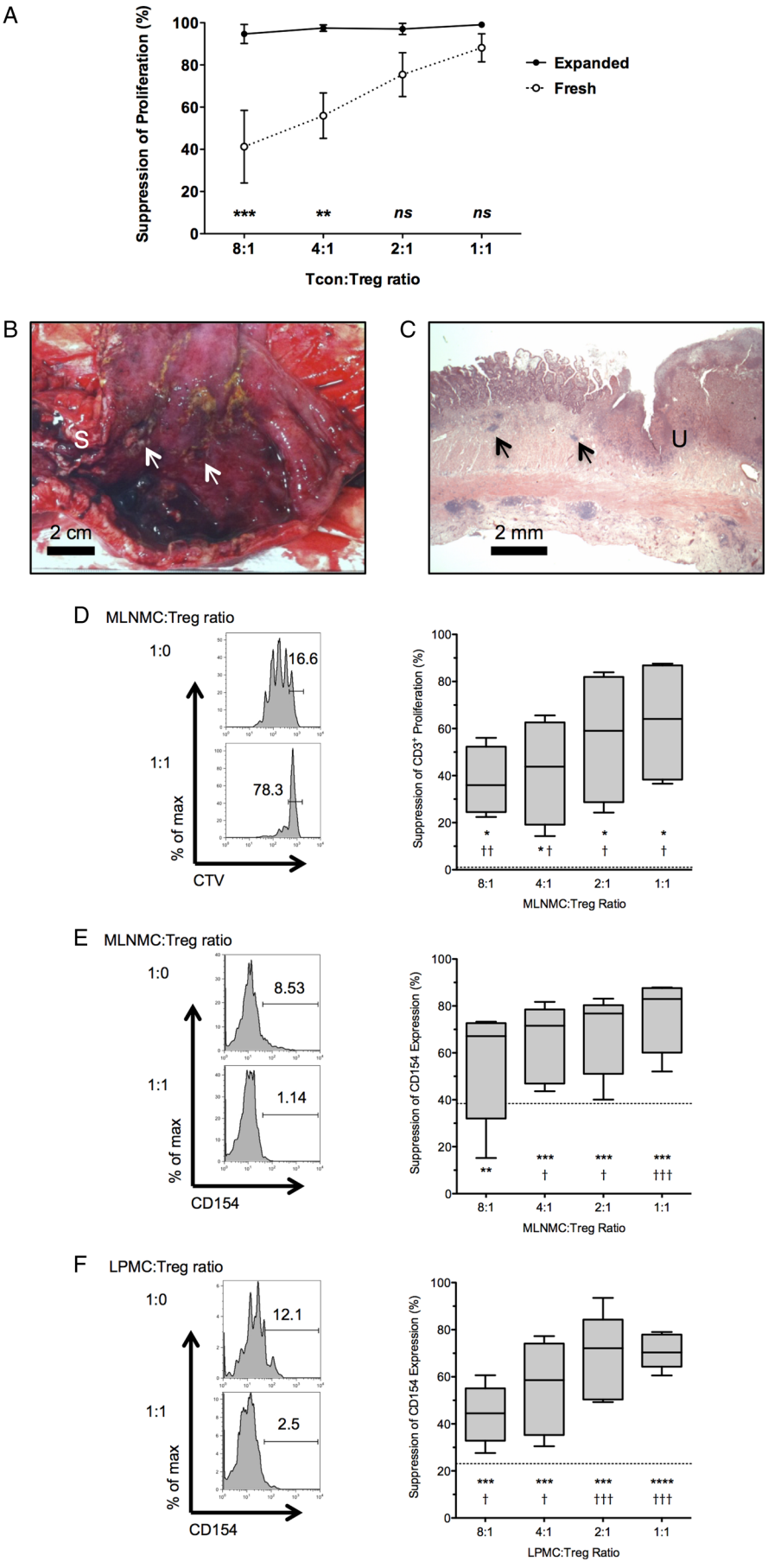

Figure 4 In vitro expanded CD45RA$^+$ T_{regs} suppress CD3$^+$ T cell responses from inflamed Crohn's MLN and LP. (A) Suppression of proliferation of a single lot of freeze-thawed, allogeneic T_{cons} by freshly isolated PB CD4$^+$CD25^{hi}CD127^{lo}CD45RA$^+$ T_{regs}, or D24 CD45RA$^+$ T_{regs} that were expanded in vitro from these freshly isolated precursors. Pooled data from three sets of freshly isolated PB T_{regs} and subsequently expanded T_{reg} populations. Data points are mean ±SEM. (B) Fresh ileal resection specimen opened longitudinally to show ileal stricture (marked 'S') and proximal inflamed, haemorrhagic mucosa with deep ulceration (arrows). Scale bar: 2 cm. (C) Representative microscopic image from this resection showing mucosal distortion, ulceration (marked 'U') and transmural inflammation, including lymphoid aggregates (arrows). 12.5× H&E. Scale bar: 2 mm. (D) Representative FACS plots gated on live CD3$^+$ events, showing proliferation of MLN T_{cons} cultured alone (top left panel) or with T_{regs} at a 1:1 MLNMC:T_{reg} ratio (bottom left panel). Pooled data showing T_{reg}-mediated suppression of MLN CD3$^+$ proliferation (right panel, n=5). Box and whisker plot shows median, IQR and range. (E) Representative FACS plots gated on live MLN CD3$^+$ events showing CD154 expression on MLN T_{cons} cultured alone (top left panel) or with T_{regs} at a 1:1 MLNMC:T_{reg} ratio (bottom left panel). Pooled data showing T_{reg}-mediated suppression of CD154 expression in live MLN CD3$^+$ cells (right panel, n=5). (F) Representative FACS plots gated on live LP CD3$^+$ events showing CD154 expression on LP T_{cons} cultured alone (top left panel) or with T_{regs} at a 1:1 LPMC:T_{reg} ratio (bottom left panel). Pooled data showing T_{reg}-mediated suppression of CD154 expression in live LP CD3$^+$ cells (right panel, n=5). (D–F) Dotted line shows non-specific suppression from '2X control'. Comparisons between observed suppression and non-specific suppression (†p<0.05, ††p<0.01, †††p<0.001, ††††p<0.0001) and observed suppression and no suppression (zero, *p<0.05, **p<0.01, ***p<0.001 and ****p<0.0001) are shown. T_{regs}, thymus-derived regulatory T cells; MLN, Mesenteric lymph node; LP, lamina propria; T_{cons}, conventional CD4$^+$CD25$^{lo/int}$ T cells; PB, peripheral blood; FACS, fluorescence-activated cell sorting; MLNMC, MLN mononuclear cell; LPMC, LP mononuclear cell; CTV, Cell Trace Violet.

at 96h[25 49] Significant dose-dependent suppression of CD154 expression in MLN and LP T cells was observed (figure 4E, F), demonstrating that in vitro expanded D24 CD45RA$^+$ T_{regs} suppress early activation of MLN and LP T_{cons} in vitro.

DISCUSSION

There remains an unmet need to develop novel therapies for CD, as current drug treatments frequently fail to maintain long-term remission and may be complicated by significant side effects. Cellular therapies are emerging as potentially attractive therapeutic strategies. T_{regs} are effective in preclinical models of colitis[2 6] and phase 1 clinical trials suggest that in vitro expanded T_{regs} are safe in the prophylaxis and treatment of GvHD[12 24] and type 1 diabetes.[18] We built on recent work to describe a method for isolation and expansion of T_{regs} from Crohn's blood that is readily transferable to a GMP background and addresses several barriers to the use of expanded T_{regs} as an autologous cell-based therapy in this important disease.

T_{regs} can be selected and expanded in vitro to clinically useful numbers under both R&D-grade,[11 13 16 21 23 26] and GMP conditions[12 18 24] retaining an in vitro suppressive function before infusion into humans. We showed that it is feasible to do the same using T_{regs} obtained from Crohn's blood, including patients receiving thiopurines or anti-tumor necrosis factor (TNF) medications. Even after prolonged culture, these T_{regs} maintained FOXP3 expression and suppressed activation of autologous T cells.

T cell lineage plasticity is well described. A major potential barrier to T_{reg} therapy is the possibility that these cells might adopt an inflammatory phenotype and worsen inflammation on adoptive transfer. Freshly isolated thymus-derived T_{regs} from both mice and humans can express proinflammatory cytokines and transcription factors (TF) canonical to effector CD4$^+$ lineages, including IL-17[39–41] and IFN-γ,[44] both of which are implicated in CD pathogenesis. Indeed, IL-17$^+$FOXP3$^+$ T_{regs} have been identified in non-inflamed human blood and lymphoid tissue,[40] and inflamed Crohn's mucosa.[43] While there is some evidence that plastic cytokine and TF expression may license efficient T_{reg} homing to, and suppression of, Th1-mediated and Th17-mediated inflammation,[44 56] this may also lead to the generation of T_{regs} with an effector phenotype that contribute to inflammation.

We and others have demonstrated that in vitro expanded T_{regs} cultured in the presence of rapamycin have enhanced phenotypic stability.[13 21] We show that as well as retaining their suppressive capacity, CD45RA$^+$ rT_{regs} expanded from the blood of patients with CD in the presence of rapamycin do not express IL-17A or other Th17-related genes, even following exposure to proinflammatory cytokines that they would likely meet in inflamed intestinal mucosa. These data corroborate data from Hoffmann *et al*[17 47] in healthy controls, showing that expanded CD45RA$^+$ T_{regs} are resistant to the induction of proinflammatory cytokines on stimulation and highly express CD62L and CCR7, which are associated with phenotypic stability.

Freshly isolated CD45RA$^+$ rT_{regs} have an epigenetically stable *FOXP3* locus with extensive TSDR demethylation.[46] TSDR demethylation correlates with stable FOXP3 expression in vitro[50] and T_{reg}-mediated protection from autoimmunity in vivo[57] in humans. However, the significance of TSDR demethylation for in vitro expanded T_{regs} is poorly understood. Barzaghi *et al*[57] recently described a cohort of patients with 'Immune dysregulation, Polyendocrinopathy, Enteropathy, X-linked syndrome (IPEX)-like syndrome', severe multisystem autoimmunity in the absence of identifiable mutations in molecules implicated in T_{reg} function, with decreased TSDR demethylation despite normal T_{reg} numbers and in vitro suppression. This suggests that ex vivo expanded CD45RA$^-$ T_{regs}, with incomplete TSDR demethylation, may have suboptimal biological activity in vivo, despite suppressive function in vitro. These data also suggest that CD45RA$^+$ T_{regs} are more likely to retain phenotypic stability and are less likely to acquire an effector phenotype than CD45RA$^-$ T_{regs}, consistent with a more favourable safety profile of this T_{reg} subset as a cell-based therapy for CD.

In order to be therapeutically effective, adoptively transferred T_{regs} may need to traffic to intestinal lymphoid tissue or LP. Some groups have taken advantage of TCRs specific for luminal antigens to direct T_{regs} to the intestinal mucosa, such as IL-10-producing T cell clones with ovalbumin-specific TCRs,[58] or T cells with transgenic Cbir1 flagellin-specific TCRs.[59] Alternatively, T_{reg} expansion in the presence of ATRA induces $\alpha_4\beta_7$ integrin expression but also increases effector cytokine expression, such as IL-17 and IFN-γ, potentially limiting its use in GMP cell expansion.[13 21] We show that CD45RA$^+$ T_{regs} expanded in the presence of IL-2 and rapamycin highly express CD62L and CCR7, allowing homing to, and anatomical orientation within lymphoid tissue.[60 61] T_{reg} CD62L expression is also required for T_{reg}-mediated cure of GvHD.[30] CD45RA$^+$ T_{regs} also expressed CCR4, required for T_{reg}-mediated prevention of CD45RB^{hi} colitis.[62] Interestingly, murine T_{regs} do not need to home to intestinal LP to prevent CD45RB^{hi} adoptive transfer colitis. β_7 integrin-null T_{regs} home to MLN and prevent colitis in this model, despite almost undetectable LP homing.[63] Consequently, the ability to home to MLN is highly desirable in potentially therapeutic cells.

CD45RA$^+$ T_{regs} also express $\alpha_4\beta_7$ integrin and CXC motif receptor 3 (CXCR3), indicating an ability to home to LP and sites of inflammation, respectively. Moreover, we used a human small intestinal xenotransplant model to show, for the first time, that in vitro expanded CD45RA$^+$ T_{regs} from patients with CD home to inflamed human gut in vivo. Xenotransplanted SB segments develop into tissue that is morphologically and functionally identical to normal gut and is capable of peristalsis and nutrient absorption.[53 54] The xenografts also possess a chimeric endothelium that expresses human MadCAM-1.[64] This is the first demonstration that this model can be used in the assessment of immune cell homing.

Xenograft-bearing mice received rhIL-2 in order to support survival of adoptively transferred human T_{regs},[23] as murine IL-2 is less efficient at promoting proliferation of human T cells than rhIL-2, despite cross-reactivity.[65] As recent phase 1 trials of in vitro expanded T_{regs} in GvHD and type 1 diabetes mellitus showed signs of clinical efficacy without supplemental rhIL-2, it is likely that this is a feature of the experimental system and will not be required in clinical trials in Inflammatory bowel disease (IBD).[12 18 24]

Future work will include 'humanising' xenograft-bearing mice and developing additional techniques to induce xenograft inflammation, thus allowing us to assess the functional impact of CD45RA$^+$ T_{regs} on gut inflammation. The percentage of LP human T cells that could be recovered from human bowel transplants was relatively modest compared with the percentage of T cells recovered from the spleen. Given that the expression of the gut homing integrin $\alpha_4\beta_7$ was only expressed on ~20% of the purified T_{regs}, future work may need to address methods to increase $\alpha_4\beta_7$ expression, such as the use of retinoic acid, as we have previously shown.[21]

An additional barrier to T_{reg} therapy in CD is that effector T cells from the diseased mucosa of patients with CD may be resistant to the suppressive action of T_{regs}. Indeed, we previously

showed that T_{cons} isolated from inflamed Crohn's mucosa are relatively resistant to T_{reg}-mediated suppression, due to overexpression of Smad7, an inhibitor of TGF-β signalling.[35 36] In this study, we utilised T_{regs} cultured in the presence of rapamycin, which has been shown to enhance the suppressive ability of in vitro expanded T_{regs}, compared with T_{regs} freshly isolated from the same donor[26 38] and show that in vitro expansion enhances the suppressive ability of T_{regs} obtained from CD PB. Rapamycin-expanded CD45RA$^+$ T_{regs} effectively suppress both MLN and LP T cells obtained from inflamed Crohn's resection specimens. These data suggest that in vitro expanded CD45RA$^+$ T_{regs} may modulate immune responses in niches directly relevant to the pathogenesis of CD. T_{regs} use multiple mechanisms to suppress in vitro and in vivo, including contact-dependent mechanisms (CTLA-4, perforin-granzyme B) and contact-independent mechanisms (IL-10, TGF-β, extracellular ATPase activity via CD39/CD73,etc). Sakaguchi *et al*[10] has proposed a multistep model of in vitro suppression that initially requires cell-cell contact but is subsequently contact independent. The mechanism of suppression of erstwhile 'resistant' mucosal T_{cons} by in vitro expanded T_{regs} is currently unknown and will be the subject of further study. In addition, not all of the patients in this study had active disease, so it will be important to extend these data further to broaden the therapeutic relevance of these findings. However, a substantial proportion of the patients in this study did have evidence of disease activity (n=5/13), which did not affect either T_{reg} expansion or function.

In conclusion, we have shown that in vitro expanded CD45RA$^+$ T_{regs} are likely to be the most suitable T_{reg} subset for cellular therapeutics in CD. This subset is readily expandable to sufficiently high numbers under conditions that are readily transferable to GMP, for clinical use. They express an appropriate repertoire of homing receptors for MLN and gut, and effectively traffic to inflamed gut in vivo. As well as retaining powerful suppressive properties, these cells show little or no capacity for plasticity towards a potentially harmful effector phenotype, which correlates with an epigenetically stable *FOXP3* locus. This study addresses many of the perceived barriers to T_{reg} cell treatment for CD and paves the way for a clinical trial of in vitro expanded CD45RA$^+$ T_{regs} in this therapeutically challenging disease.

Author affiliations
[1]Medical Research Council Centre for Transplantation, King's College London, London, UK
[2]Department of Experimental Immunobiology, King's College London, London, UK
[3]National Institute for Health Research Biomedical Research Centre at Guy's and St. Thomas' NHS Foundation Trust and King's College London, London, UK
[4]Department of Gastroenterology, Guy's & St Thomas' NHS Foundation Trust, London, UK
[5]Department of Immunoregulation and Immune Intervention, King's College London, London, UK
[6]Blizard Institute, Barts and the London School of Medicine and Dentistry, London, UK
[7]The Koret School of Veterinary Medicine, Hebrew University of Jerusalem, Rehovot, Israel
[8]Division of Diabetes and Nutritional Sciences, King's College London, London, UK
[9]Department of Obstetrics & Gynaecology, Hadassah University Hospital, Jerusalem, Israel

Correction notice This article has been corrected since it published online first. The results section has been updated.

Contributors JBC designed and executed the experiments, analysed and interpreted the data and wrote the manuscript. MJE, IS, AV, CS, RG, EM and JWL designed and executed experiments and contributed to the manuscript. ES, NP, HF and JKH provided intellectual input and contributed to the manuscript. JBC, GML, PMI, JDS and SY developed the research infrastructure and governance for human sample collection. PMI, JDS and SY provided ongoing clinical care and intellectual input, and contributed to the manuscript. TTM, MPH-F, NYS and GL designed the experiments, interpreted data and wrote the manuscript. GML is the senior author and guarantor of this manuscript.

Funding This study was supported by grants awarded by the National Institute for Health Research (JBC, GML; grant number DRF/2009/02/22), Guy's and St Thomas' Charity (JBC, MPH-F, JDS, GML; grant number R090707), the Academy of Medical Sciences (JBC; Daniel Turnberg Memorial Fund) the Medical Research Council, UK (GML, TTM; grant number G0802068; GML, JKH, grant number MR/K002996/1; MPH-F, grant numbers G0801537/ID: 88245 and MR/J006742/1), the Wellcome Trust (NP, GML, TTM, grant number WT088747MA, GML, grant number 091009), the European Union 7th Framework Programme (EU FP7) (GLom, CS, MPH-F; The ONE study; reference 260687; MPH-F; BIO-DRIM; reference 305147) and King's Health Partners Research and Development Challenge Fund, Guy's and St Thomas' Charity (CS; grant number R1405170). Research was also supported by the National Institute for Health Research (NIHR) Biomedical Research Centre based at Guy's and St Thomas' National Health Service (NHS) Foundation Trust and King's College London. The views expressed are those of the author(s) and not necessarily those of the NHS, the NIHR, or the Department of Health.

Competing interests None.

Ethics approval South East London REC 2 (10/H0804/65). East London REC 2 (10/H0704/74). Ethics Committee for Animal Experimentation, Hebrew University of Jerusalem (MD-11-12692-4). Helsinki Committee of the Hadassah University Hospital (81-23/04/04).

Provenance and peer review Not commissioned; externally peer reviewed.

Data sharing statement All available data are included in this manuscript.

REFERENCES

1 Veltkamp C, Ruhwald R, Giesem T, *et al*. CD4+CD25+ cell depletion from the normal CD4+ T cell pool prevents tolerance toward the intestinal flora and leads to chronic colitis in immunodeficient mice. *Inflamm Bowel Dis* 2006;12:437–46.
2 Powrie F, Leach MW, Mauze S, *et al*. Phenotypically distinct subsets of CD4+ T cells induce or protect from chronic intestinal inflammation in C. B-17 scid mice. *Int Immunol* 1993;5:1461–71.
3 Morrissey PJ, Charrier K, Braddy S, *et al*. CD4+ T cells that express high levels of CD45RB induce wasting disease when transferred into congenic severe combined immunodeficient mice. Disease development is prevented by cotransfer of purified CD4+ T cells. *J Exp Med* 1993;178:237–44.
4 Maloy KJ, Salaun L, Cahill R, *et al*. CD4+CD25+ T(R) cells suppress innate immune pathology through cytokine-dependent mechanisms. *J Exp Med* 2003;197:111–19.
5 Mottet C, Uhlig HH, Powrie F. Cutting edge: cure of colitis by CD4+CD25+ regulatory T cells. *J Immunol* 2003;170:3939–43.
6 Garrett WS, Lord GM, Punit S, *et al*. Communicable ulcerative colitis induced by T-bet deficiency in the innate immune system. *Cell* 2007;131:33–45.
7 Watanabe K, Rao VP, Poutahidis T, *et al*. Cytotoxic-T-lymphocyte-associated antigen 4 blockade abrogates protection by regulatory T cells in a mouse model of microbially induced innate immune-driven colitis. *Infect Immun* 2008;76:5834–42.
8 Wildin RS, Ramsdell F, Peake J, *et al*. X-linked neonatal diabetes mellitus, enteropathy and endocrinopathy syndrome is the human equivalent of mouse scurfy. *Nat Genet* 2000;27:18–20.
9 Brunkow ME, Jeffery EW, Hjerrild KA, *et al*. Disruption of a new forkhead/winged-helix protein, scurfin, results in the fatal lymphoproliferative disorder of the scurfy mouse. *Nat Genet* 2001;27:68–73.
10 Sakaguchi S, Wing K, Onishi Y, *et al*. Regulatory T cells: how do they suppress immune responses? *Int Immunol* 2009;21:1105–11.
11 Battaglia M, Stabilini A, Migliavacca B, *et al*. Rapamycin promotes expansion of functional CD4+CD25+FOXP3+ regulatory T cells of both healthy subjects and type 1 diabetic patients. *J Immunol* 2006;177:8338–47.
12 Brunstein CG, Miller JS, Cao Q, *et al*. Infusion of ex vivo expanded T regulatory cells in adults transplanted with umbilical cord blood: safety profile and detection kinetics. *Blood* 2011;117:1061–70.
13 Golovina TN, Mikheeva T, Brusko TM, *et al*. Retinoic acid and rapamycin differentially affect and synergistically promote the ex vivo expansion of natural human T regulatory cells. *PLoS ONE* 2011;6:e15868–8.
14 Hippen KL, Merkel SC, Schirm DK, *et al*. Massive ex vivo expansion of human natural regulatory T cells (T(regs)) with minimal loss of in vivo functional activity. *Sci Transl Med* 2011;3:83ra41.
15 Hippen KL, Merkel SC, Schirm DK, *et al*. Generation and large-scale expansion of human inducible regulatory T cells that suppress graft-versus-host disease. *Am J Transplant* 2011;11:1148–57.

16 Hoffmann P, Eder R, Kunz-Schughart LA, *et al*. Large-scale in vitro expansion of polyclonal human CD4(+)CD25high regulatory T cells. *Blood* 2004;104:895–903.
17 Hoffmann P, Eder R, Boeld TJ, *et al*. Only the CD45RA+ subpopulation of CD4+CD25high T cells gives rise to homogeneous regulatory T-cell lines upon in vitro expansion. *Blood* 2006;108:4260–7.
18 Marek-Trzonkowska N, Mysliwiec M, Dobyszuk A, *et al*. Administration of CD4+CD25highCD127- regulatory T cells preserves β-cell function in type 1 diabetes in children. *Diabetes Care* 2012;35:1817–20.
19 Putnam AL, Safinia N, Medvec A, *et al*. Clinical grade manufacturing of human alloantigen-reactive regulatory T cells for use in transplantation. *Am J Transplant* 2013;13:3010–20.
20 Putnam AL, Brusko TM, Lee MR, *et al*. Expansion of human regulatory T-cells from patients with type 1 diabetes. *Diabetes* 2009;58:652–62.
21 Scottà C, Esposito M, Fazekasova H, *et al*. Differential effects of rapamycin and retinoic acid on expansion, stability and suppressive qualities of human CD4(+)CD25(+)FOXP3(+) T regulatory cell subpopulations. *Haematologica* 2013;98:1291–9.
22 Strauss L, Czystowska M, Szajnik M, *et al*. Differential responses of human regulatory T cells (Treg) and effector T cells to rapamycin. *PLoS ONE* 2009;4:e5994.
23 Tresoldi E, Dell'Albani I, Stabilini A, *et al*. Stability of human rapamycin-expanded CD4+CD25+ T regulatory cells. *Haematologica* 2011;96:1357–65.
24 Trzonkowski P, Bieniaszewska M, Juścińska J, *et al*. First-in-man clinical results of the treatment of patients with graft versus host disease with human ex vivo expanded CD4+CD25+CD127− T regulatory cells. *Clin Immunol* 2009;133:22–6.
25 Canavan JB, Afzali B, Scottà C, *et al*. A rapid diagnostic test for human regulatory T-cell function to enable regulatory T-cell therapy. *Blood* 2012;119:e57–66.
26 Afzali B, Edozie FC, Fazekasova H, *et al*. Comparison of regulatory T cells in hemodialysis patients and healthy controls: implications for cell therapy in transplantation. *Clin J Am Soc Nephrol* 2013;8:1396–405.
27 Issa F, Hester J, Goto R, *et al*. Ex vivo-expanded human regulatory T cells prevent the rejection of skin allografts in a humanized mouse model. *Transplantation* 2010;90:1321–7.
28 Sagoo P, Ali N, Garg G, *et al*. Human regulatory T cells with alloantigen specificity are more potent inhibitors of alloimmune skin graft damage than polyclonal regulatory T cells. *Sci Transl Med* 2011;3:83ra42–2.
29 Nadig SN, Wieckiewicz J, Wu DC, *et al*. *In vivo* prevention of transplant arteriosclerosis by ex vivo–expanded human regulatory T cells. *Nat Med* 2010;16:809–13.
30 Ermann J, Hoffmann P, Edinger M, *et al*. Only the CD62L+ subpopulation of CD4+CD25+ regulatory T cells protects from lethal acute GVHD. *Blood* 2005;105:2220–6.
31 Leslie M. Immunology. Regulatory T cells get their chance to shine. *Science* 2011;332:1020–1.
32 Maul J, Loddenkemper C, Mundt P, *et al*. Peripheral and intestinal regulatory CD4+CD25(high) T cells in inflammatory bowel disease. *Gastroenterology* 2005;128:1868–78.
33 Saruta M, Yu QT, Fleshner PR, *et al*. Characterization of FOXP3+CD4+ regulatory T cells in Crohn's disease. *Clin Immunol* 2007;125:281–90.
34 Reikvam DH, Perminow G, Lyckander LG, *et al*. Increase of regulatory T cells in ileal mucosa of untreated pediatric Crohn's disease patients. *Scand J Gastroenterol* 2011;46:550–60.
35 Fantini MC, Rizzo A, Fina D, *et al*. Smad7 controls resistance of colitogenic T cells to regulatory T cell-mediated suppression. *Gastroenterology* 2009;136:1308–16, e1–3.
36 Monteleone G, Del Vecchio Blanco G, Monteleone I, *et al*. Post-transcriptional regulation of Smad7 in the gut of patients with inflammatory bowel disease. *Gastroenterology* 2005;129:1420–9.
37 Afzali B, Mitchell PJ, Scottà C, *et al*. Relative resistance of human CD4(+) memory T cells to suppression by CD4(+) CD25(+) regulatory T cells. *Am J Transplant* 2011;11:1734–42.
38 Cao T, Wenzel SE, Faubion WA, *et al*. Enhanced suppressive function of regulatory T cells from patients with immune-mediated diseases following successful ex vivo expansion. *Clin Immunol* 2010;136:329–37.
39 Koenen HJPM, Smeets RL, Vink PM, *et al*. Human CD25highFoxp3pos regulatory T cells differentiate into IL-17-producing cells. *Blood* 2008;112:2340–52.
40 Voo KS, Wang Y-H, Santori FR, *et al*. Identification of IL-17-producing FOXP3+ regulatory T cells in humans. *Proc Natl Acad Sci USA* 2009;106:4793–8.
41 Afzali B, Mitchell PJ, Edozie FC, *et al*. CD161 expression characterizes a subpopulation of human regulatory T cells that produces IL-17 in a STAT3-dependent manner. *Eur J Immunol* 2013;43:2043–54.
42 Bettelli E, Carrier Y, Gao W, *et al*. Reciprocal developmental pathways for the generation of pathogenic effector TH17 and regulatory T cells. *Nature* 2006;441:235–8.
43 Hovhannisyan Z, Treatman J, Littman DR, *et al*. Characterization of interleukin-17-producing regulatory T cells in inflamed intestinal mucosa from patients with inflammatory bowel diseases. *Gastroenterology* 2011;140:957–65.
44 Koch MA, Tucker-Heard G, Perdue NR, *et al*. The transcription factor T-bet controls regulatory T cell homeostasis and function during type 1 inflammation. *Nat Immunol* 2009;10:595–602.
45 Oldenhove G, Bouladoux N, Wohlfert EA, *et al*. Decrease of Foxp3^{+} Treg cell number and acquisition of effector cell phenotype during lethal infection. *Immunity* 2009;31:772–86.
46 Miyara M, Yoshioka Y, Kitoh A, *et al*. Functional delineation and differentiation dynamics of human CD4^{+} T cells expressing the FoxP3 transcription factor. *Immunity* 2009;30:899–911.
47 Hoffmann P, Boeld TJ, Eder R, *et al*. Loss of FOXP3 expression in natural human CD4+CD25+ regulatory T cells upon repetitive in vitro stimulation. *Eur J Immunol* 2009;39:1088–97.
48 Schmidl C, Hansmann L, Andreesen R, *et al*. Epigenetic reprogramming of the RORC locus during in vitro expansion is a distinctive feature of human memory but not naïve Treg. *Eur J Immunol* 2011;41:1491–8.
49 Canavan JB, Afzali B, Lord GM, *et al*. Assessment of regulatory T-cell function in forthcoming clinical trials of cell therapy. *Expert Rev Mol Diagn* 2013;13:5–7.
50 Polansky JK, Kretschmer K, Freyer J, *et al*. DNA methylation controls Foxp3 gene expression. *Eur J Immunol* 2008;38:1654–63.
51 Sehouli J, Loddenkemper C, Cornu T, *et al*. Epigenetic quantification of tumor-infiltrating T-lymphocytes. *Epigenetics* 2011;6:236–46.
52 Powell N, Walker AW, Stolarczyk E, *et al*. The transcription factor T-bet regulates intestinal inflammation mediated by interleukin-7 receptor+ innate lymphoid cells. *Immunity* 2012;37:674–84.
53 Howie D, Spencer J, DeLord D, *et al*. Extrathymic T cell differentiation in the human intestine early in life. *J Immunol* 1998;161:5862–72.
54 Golan L, Gonen E, Yagel S, *et al*. Enterohemorrhagic *Escherichia coli* induce attaching and effacing lesions and hemorrhagic colitis in human and bovine intestinal xenograft models. *Dis Model Mech* 2010;4:86–94.
55 Strauss L, Whiteside TL, Knights A, *et al*. Selective survival of naturally occurring human CD4+CD25+Foxp3+ regulatory T cells cultured with rapamycin. *J Immunol* 2007;178:320–9.
56 Chaudhry A, Rudra D, Treuting P, *et al*. CD4+ regulatory T cells control TH17 responses in a Stat3-dependent manner. *Science* 2009;326:986–91.
57 Barzaghi F, Passerini L, Gambineri E, *et al*. Journal of autoimmunity. *J Autoimmun* 2012;38:49–58.
58 Desreumaux P, Foussat A, Allez M, *et al*. Safety and efficacy of antigen-specific regulatory T-cell therapy for patients with refractory Crohn's disease. *Gastroenterology* 2012;143:1207–17.e1–2.
59 Feng T, Cao AT, Weaver CT, *et al*. Interleukin-12 converts Foxp3+ regulatory T cells to interferon-γ-producing Foxp3+ T cells that inhibit colitis. *Gastroenterology* 2011;140:2031–43.
60 Debes GF, Höpken UE, Hamann A. In vivo differentiated cytokine-producing CD4(+) T cells express functional CCR7. *J Immunol* 2002;168:5441–7.
61 Zhang N, SchrOppel B, Lal G, *et al*. Regulatory T cells sequentially migrate from inflamed tissues to draining lymph nodes to suppress the alloimmune response. *Immunity* 2009;30:458–69.
62 Yuan Q, Bromley SK, Means TK, *et al*. CCR4-dependent regulatory T cell function in inflammatory bowel disease. *J Exp Med* 2007;204:1327–34.
63 Denning TL, Kim G, Kronenberg M. Cutting edge: CD4+CD25+ regulatory T cells impaired for intestinal homing can prevent colitis. *J Immunol* 2005;174:7487–91.
64 Winter HS, Hendren RB, Fox CH, *et al*. Human intestine matures as nude mouse xenograft. *Gastroenterology* 1991;100:89–98.
65 Mosmann TR, Yokota T, Kastelein R, *et al*. Species-specificity of T cell stimulating activities of IL 2 and BSF-1 (IL 4): comparison of normal and recombinant, mouse and human IL 2 and BSF-1 (IL 4). *J Immunol* 1987;138:1813–16.