Dietary environmental factors shape the defence against infection with *Cryptosporidium*

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SUMMARY

Cryptosporidium is a leading cause of diarrheal-related deaths in children, especially in resource-poor settings. It also targets the immunocompromised, chronically infecting people living with HIV and primary immunodeficiencies. There is no vaccine or effective treatment. While it is known from human cases and animal models that $CD4^+$ T-cells play a role in curbing *Cryptosporidium*, the role of $CD8^+$ cells remains to be defined. Using a *Cryptosporidium tyzzeri* mouse model, we show that gut-resident $CD8^+$ intraepithelial lymphocytes (IELs) confer resistance to parasite growth. $CD8^+$ IELs express, and are dependent on, the ligand-dependent transcription factor aryl hydrocarbon receptor (AHR). AHR deficiency reduced $CD8^+$ IELs, decreased their cytotoxicity, and worsened infection. Transfer of $CD8^+$ IELs rescued severely immunodeficient mice from death following *Cryptosporidium* challenge. Finally, dietary supplementation of the AHR pro-ligand, indole-3-carbinol, to new-born mice promoted resistance to infection. Therefore, common dietary metabolites augment the host immune response to cryptosporidiosis, protecting against disease.

KEYWORDS: *Cryptosporidium*, intraepithelial lymphocytes, aryl hydrocarbon receptor, indole-3-carbinol, diet.

INTRODUCTION

Diarrhoea contributes to nearly 11% of early childhood mortality worldwide (Liu et al., 2012). *Cryptosporidium* is an apicomplexan parasite that invades epithelial cells of the small intestine (Guerin and Striepen, 2020) and its infections are the second-leading cause of severe diarrhoeal events in young children in resource-poor regions (Kotloff 2013). Recurrent infections are associated with malnutrition, leading to lasting effects such as growth stunting and impaired cognitive development (Kabir et al., 2021; Khalil et al., 2018; Molbak et al., 1997). It is also an important opportunistic pathogen in immunocompromised individuals such as people living with HIV, transplant and chemotherapy recipients, and patients undergoing treatment for haemodialysis and cancer (Manabe et al., 1998; Sepahvand et al., 2022). Human cryptosporidiosis is usually caused by anthroponotic *Cryptosporidium hominis* or zoonotic *Cryptosporidium parvum* (Hossain et al., 2019). There is no vaccine against cryptosporidiosis. Nitazoxanide, the only FDA approved drug to treat cryptosporidiosis, has limited efficacy in immunocompetent individuals and is ineffective in HIV-AIDS patients and malnourished individuals (Amadi et al., 2002; Amadi et al., 2009). Although some progress has been made towards development of new therapeutics (Manjunatha et al., 2017), this has been hindered by a lack of physiologically relevant model systems of cryptosporidiosis (Manjunatha et al., 2017; Marzook and Sateriale, 2020). We previously developed a mouse model of cryptosporidiosis with a natural mouse-infecting species, *Cryptosporidium tyzzeri,* which recapitulates the natural course of infection and intestinal pathology of human disease (Sateriale et al., 2019).

Increased susceptibility of patients with primary immunodeficiencies and experimental infections of human volunteers suggests an immune system-mediated protection from cryptosporidiosis (Cohn et al., 2022). Furthermore, most children living in

endemic regions develop protective immunity to subsequent infections (Kabir et al., 2021; Kattula et al., 2017). Early studies on athymic mice revealed T-cells as important regulators of *C. parvum* infection (Heine et al., 1984). Increased infection burden in HIV-AIDS patients with low CD4+ T cell counts also highlights the importance of IFNg-producing CD4+ T cells (Kaplan et al., 2009). Mice lacking T-cells (but not B cells) are unable to control a *C. tyzzeri* infection (Sateriale et al., 2019). Furthermore, mice without mature T and B cells, and those lacking IFNg, cannot elicit vaccination-mediated protection during a secondary parasite infection (Sateriale et al., 2019). Mice harbouring a commensal strain of *C. tyzzeri* elicit both innate and adaptive immune responses, with early evidence hinting at elevated CD8+ T cells in infected mice (Russler-Germain et al., 2021). $CD8^+$ T cells are highly enriched in the intestine and notably heterogeneous in phenotype and function. 'Conventional' mucosal T cells express TCRαβ together with CD4 or CD8αβ as TCR coreceptors and reside in the lamina propria. 'Non-conventional' mucosal T cells, expressing either TCRαβ or TCRγδ and typically also CD8αα homodimers, are prevalent in the mucosal epithelium (Hayday et al., 2001; Sujino et al., 2016). Thymic-derived natural intraepithelial lymphocytes (IELs) express CD8αα (TCRαβ+CD8αα, TCRαβ+CD4+CD8αα and TCRγδ CD8αα), whereas peripherally induced IELs express CD8αβ (TCRαβ+CD8αβ) (Cheroutre et al., 2011; Hoytema van Konijnenburg and Mucida, 2017).

$CD8^+$ IELs cells constantly scan epithelial cells for injury or infection and are considered primary responders to epithelial damage (Hoytema van Konijnenburg et al., 2017). $CD8^+$ IELs are elevated in calves and mice infected with *C. parvum* (Chai et al., 1999; Pasquali et al., 1997). Nevertheless, factors that influence $CD8^+$ IEL- mediated immunity and mechanisms by which $CD8^+$ IELs confer resistance to *Cryptosporidium* are unknown. Most CD8+ T cells exhibit a tissue-resident memory phenotype (Sasson et al., 2020) and their maintenance depends on

stimulation of the aryl hydrocarbon receptor (AHR) by endogenous ligands such as tryptophan-derived phytochemicals, microbial metabolites, and indole derivatives (Li et al., 2011) . AHR is a ligand-dependent transcription factor abundantly expressed in barrier tissues such as the gut, skin, and lungs. AHR is expressed by various cells in the gut including barrier epithelium, endothelium, and immune cells, and is hence a key factor in maintaining gut barrier integrity (Stockinger et al., 2021). AHR deficiency or depletion of AHR ligands increases susceptibility to bacterial infection in the colon (Stockinger et al., 2021) and also contributes to colon tumorigenesis (Metidji et al., 2018).

Cryptosporidium infects and replicates inside small intestinal epithelial cells, causing villus blunting and crypt hyperplasia and thereby significant gut damage (Sateriale et al., 2019). In human volunteers infected with *C. hominis* or *C. parvum,* increased fecal indole levels prior to infection correlated with decreased parasite burden (Chappell et al., 2016), indicating a protective function of indoles in cryptosporidiosis through an unknown mechanism. We wondered if these indoles were working via AHR-mediated gut protection.

To test this, we created a novel *C. tyzzeri* reporter strain expressing luminescent and fluorescent proteins utilizing an isolate of *C. tyzzeri* from the Czech Republic (*Ct*-CR2206, shortened here to *Ct*-CR) (Kvac et al., 2013). Here we show that in immunocompetent wild-type mice, *Ct*-CR altered epithelial differentiation and triggered an expansion of $CD8^+$ IELs, and IELs conferred protection against infection when transferred to immunodeficient mice. Immune cell-specific deletion of AHR or the deprivation of AHR ligands in mice greatly depleted CD8+ IELs. Furthermore, dietary supplementation of AHR ligands to nursing mothers and their weaned pups provided prophylactic defence against infection. This highlights the opportunity for diet-based therapeutic interventions to treat this debilitating disease in humans and ruminant animals.

RESULTS

Cryptosporidium tyzzeri infects the ileum and affects epithelial cell differentiation.

The *Cryptosporidium tyzzeri* strain Ct-CR2206 was originally isolated from a wild mouse in the Věrušičky municipality of the Czech Republic (Kvac et al., 2013). We began by sequencing the genome of *Ct*-CR2206 (shortened here to '*Ct*-CR') using Illumina short read sequencing. Reads were mapped using the full *C. tyzzeri*-UGA55 genome as a reference (**Figure 1A**). In total, 13139 SNPs and 2983 insertion-deletion events were detected between the two strains (see Supplementary Table S1 for a further breakdown). We genetically engineered *Ct*-CR to express the fluorescent mNeonGreen protein, along with a Nanoluciferase and Neomycin resistance cassette for easy parasite detection and transgenic selection, respectively (**Figures 1B, 1C**). Parasite replication over time could be tracked by assaying Nanoluciferase activity in mouse fecal pellets (**Figure 1D**).

Ct-CR infects the small intestine but not the colon **(Figure 1E)** (Russler-Germain et al., 2021; Sateriale et al., 2019). To determine which specific region in the small intestine harboured parasites, we infected C57BL/6 wild-type (WT) mice and measured luciferase levels from duodenal, jejunal, and ileal tissue every other day up to day 14 post-infection (DPI-14). This revealed the ileum to be the major site of *Ct*-CR expansion within the small intestine **(Figure 1F).** This infection location is similar to the previously described US *C.tyzzeri* strain UGA55 and to what is seen during human cryptosporidiosis. Luciferase levels in fecal samples from the same mice reflected the parasite burden in the ileum **(Figure 1G)**. Therefore, we used readings from fecal samples as representative measures of the *Ct*-CR burden in the mouse ileum.

The cytokine interferon-γ (IFNγ) is key in control of *Cryptosporidium* growth, for both *C. parvum* (Griffiths et al., 1998; Gullicksrud et al., 2022; Robinson et al., 2001) and the previously isolated US *C. tyzzeri* strain, UGA55 (Sateriale et al., 2019). Consistently, infection with the *Ct*-CR strain led to a gradual increase in IFNγ transcripts in the ileum **(Figure 1H)**, suggesting that the *Ct*-CR strain is pathogenic and induces inflammation in the infected area. Sca-1 (also known as Ly6a) is a marker of mouse intestinal epithelial injury, initially identified in the context of colitis (Yui et al., 2018) and staining of ileal sections showed a significant increase in Sca-1 expression in the villi of infected mice **(Figure 1I).** To gain insights into how *Cryptosporidium* changes the epithelial cell composition in the small intestine, we purified epithelial cells at the peak of infection (DPI-6) and compared their gene expression with that of uninfected controls. Epithelial cells from infected mice showed a reduction in the stem cell signature (*Olfm4, Clu, SOX9*) **(Figure 1J)**, and reduced expression of markers for enteroendocrine cells (*Chga*) **(Figure 1K)** and Tuft cells (*Dclk1*) **(Figure 1L)**. However, no change was seen in expression of the goblet cell marker *Muc2* **(Figure 1M).** In contrast, there was an increase in the enterocyte signature (*Car4*) **(Figure 1N).** Therefore, the *Ct*-CR strain used in this study is pathogenic in nature and causes inflammation, epithelial cell injury and alteration of the composition of the villus epithelium.

Haematopoietic cell specific aryl hydrocarbon receptor-deficient mice are susceptible to *C. tyzzeri* infection.

AHR is a transcriptional regulator of genes involved in anti-microbial defence and intestinal epithelial differentiation. It has been shown to play a protective role during colonic bacterial infection and chemically-induced colon damage (Metidji et al., 2018; Shah et al., 2022; Stockinger et al., 2021). To determine whether AHR executes similar disease protective

functions in the small intestine, we infected full body AHR knockout (AHRKO^{Body}) mice with *Ct*-CR. AHRKO^{Body} mice displayed increased parasite burdens from the beginning and maintained high parasite loads throughout the course of infection (**Figure 2A** left panel), also assessed by area under the curve (AUC) (**Figure 2A** right panel). Having established the importance of AHR for *Cryptosporidium* infection control, we next wanted to know which cells were playing a role in this defence. Using AHR-reporter mice expressing AHR td-Tomato, we determined that the majority of epithelial cells express AHR (**Figure 2B)**, consistent with previous observations (Diny et al., 2022). Since *Cryptosporidium* only infects epithelial cells, we first challenged mice with an intestinal epithelial cell (IEC)-specific AHR knockout (Vil-Cre AHR$^{fl/fl}$ termed AHRKO$^{gut\ epithelium}$) with *Ct*-CR to probe whether IEC-intrinsic AHR expression influenced parasite burden. Surprisingly, we found that epithelial AHR signalling was dispensable for control of parasite growth **(Figure 2C)**. AHR is also expressed by immune cells in the gut (**Figure 2D)**. We next asked whether AHR expression in immune cells is required to limit *Ct*-CR. To achieve this, we crossed hematopoietic cell-specific Vav-Cre mice with AHR$^{fl/fl}$ mice to produce immune cell-specific AHR-deficient mice (AHRKO^{Immune}). Consistently, mice with AHR deficiency in their immune cells were highly susceptible to *Ct*-CR infection compared with littermate controls **(Figure 2E)**. Unfortunately, Vav-Cre is also expressed by endothelial cells (Joseph et al., 2013), which also express high levels of AHR. Therefore, AHRKO^{Immune} mice could simultaneously delete AHR in both their immune and endothelial cells. To account for a potential role for AHR in anti-Cryptosporidial defence via the endothelium only, we made use of a tamoxifen-inducible Cre line controlled by the cadherin 5 (Cdh5) promoter to delete AHR selectively in endothelial cells. Cdh5$^{Tam\text{-}iCre}$AHR$^{fl/fl}$ (AHRKO^{Endo}) and littermate control mice were administered with tamoxifen orally. Five days post-tamoxifen treatment, (AHRKO^{Endo}) mice were infected with *Ct*-CR, alongside a cohort of AHRKO^{immune} mice in the

same experiment. In endothelial cell-specific AHR knockout mice, *C. tyzzeri* levels were comparable to those in littermate controls, whereas the infection burden was highly increased again in AHRKO^{immune} mice **(Figure 2F)** and *C. tyzzeri* levels in the ileum of AHRKO^{immune} mice were similar to the levels in total body-AHR deficient mice (AHR^{Body}) (**Figure 2G**). Hence, these results narrowed down the importance of AHR expression specifically in immune cells to control an intestinal *C. tyzzeri* infection. Increased parasite burden in AHRKO^{Immune} mice was associated with increased expression of enterocyte markers at the expense of stem cell and Tuft cell markers **(Figure 2H)**. Taken together, AHR signalling in immune cells is vital to regulate the ability of *Cryptosporidium* to grow in intestinal epithelial cells of the small intestine.

AHR expressing CD8α intraepithelial lymphocytes respond to *C. tyzzeri* parasite infection.

Lymphocytes in the small intestine are spatially organised into intraepithelial and lamina propria layers. The intraepithelial layer is enriched with cytotoxic CD8$^+$ intraepithelial lymphocytes (IELs), which are the primary responders to epithelial damage due to their close proximity to epithelial cells (Cheroutre et al., 2011). Immunofluorescence images of mouse ileal sections show CD3$^+$ IELs in close contact with *C. tyzzeri*-infected epithelial cells **(Figure 3A)**. Using AHR-tdTomato reporter mice, we found that all the major IEL subsets, including TCRαβ$^+$CD8αα$^+$, TCRαβ$^+$CD8αβ$^+$, and TCRγδ$^+$CD8αα$^+$ express AHR-tdTomato **(Figure 3B and Figure S1).** TCRαβ and TCRγδ IELs from *Ct*-CR infected mice had increased expression of Ki67, indicative of a hyperproliferative state **(Figure 3C &D)**, which corresponded with increased numbers of IELs in *Ct*-CR infected mice **(Figure 3E)**. Moreover, IFNγ (**Figure 3F**) expressing CD8$^+$ IELs were significantly increased following *Ct*-CR infection. CD8$^+$ IELs are quiescent at steady state with minimal proliferation (**Figure 3C &D**), however they rapidly mount cytotoxic

activity to kill target cells through effector proteins such as granzymes. Indeed, all 3 major types of CD8$^+$ IELs express granzyme-B at steady state (**Figure 3G**). Therefore, IELs sense epithelial invasion by *C. tyzzeri* similar to other infection settings (Hoytema van Konijnenburg et al., 2017; Konjar et al., 2018) and respond by producing IFNγ and granzyme-B, which are effector mediators of IEL cytotoxicity.

AHR-dependent CD8α IELs confer resistance to *C. tyzzeri* infection in immunodeficient mice.

AHR expression and signalling is essential for both TCRαβ$^+$ and TCRγδ$^+$ IEL survival, maintenance, and effector function (Dean et al., 2023; Li et al., 2011; Panda et al., 2023). In line with these findings, the percentage, and total numbers of natural CD8αα IELs recovered from naïve AHRKO^{immune} mice were significantly lower compared with WT littermates whereas the numbers of TCRαβ$^+$CD8αβ$^+$ IELs were similar **(Figure 4A-C)**. During infection with *Ct*-CR, TCRαβ$^+$CD8αα$^+$ and TCRγδ$^+$CD8αα$^+$ IELs were reduced similar to what was seen in naïve mice but TCRαβ$^+$CD8αβ$^+$ IELs increased in AHRKO^{immune} mice. **(Figure 4D&E)**. AHR deficient CD8α IELs were hyper-proliferative **(Figure 4F&G)**. However, they exhibited diminished cytolytic activity indicated by decreased granzyme-B levels **(Figure 4H&I)**. Therefore, it is likely that a decrease in cytotoxic CD8$^+$ IELs in AHR deficient mice could have contributed to the increased *Ct*-CR burden.

To directly assess the protective function of CD8$^+$ IELs, we purified CD8$^+$ IELs from the small intestine of naïve WT mice and transferred them intravenously into immunodeficient Rag2-IL2Rγ-CD47 triple knockout mice which are usually highly susceptible to infections (Gullicksrud et al., 2022). Four weeks after IEL transfer, the mice were infected with *Ct*-CR **(Figure 5A)**. While untreated immunodeficient mice experienced increased severity with significant reduction in survival **(Figure 5B)**, triple knockout mice that received WT CD8$^+$ IELs survived and had reduced parasite burdens in the feces **(Figure 5C)** and ileum **(Figure 5D).** In

conclusion, AHR expression in CD8$^+$ IELs is required for their maintenance and cytotoxicity, and these CD8$^+$ IELs alone are sufficient to control *Ct*-CR parasite growth *in vivo.*

Dietary AHR ligands confer resistance to *C. tyzzeri* infection.

AHR is a ligand-activated transcription factor. In the gut, a major source of these ligands are dietary tryptophan-derived phytochemicals and tryptophan metabolites produced by the microbiota. Since AHR expressing CD8$^+$ IELs are key to anti-Cryptosporidial activity, we wanted to determine if this function is influenced by AHR-ligand availability. The phytochemical indole-3-carbinol (I3C), enriched in cruciferous vegetables, is an AHR pro-ligand that is converted to high-affinity AHR ligands upon exposure to stomach acid (Bjeldanes et al., 1991). We first asked whether dietary supplementation with I3C influences CD8$^+$ IELs. 3-week old WT mice were fed either control phytochemical-free synthetic AIN93M diet ('purified control diet') or I3C (1000 mg/kg) enriched diet ('I3C diet') for 2 weeks and infected with *Ct*-CR while they continued on the same diets (**Figure 6A).** I3C diet fed mice had reduced parasite burdens compared with the mice fed the control diet **(Figure 6B).** Enumeration of CD8$^+$ IELs in these mice indicated that I3C diet supplementation robustly increased all subsets of CD8$^+$ IELs in the small intestine **(Figure 6C)**. To demonstrate that I3C diet mediated protection from *Ct*-CR infection is T-cell dependent, we fed Rag2 knockout mice with purified control or I3C diet for 2 weeks. Infection with *Ct*-CR resulted in similar burden of parasite in both groups of mice independent of exposure to I3C diet **(Figure 6D&E)**. We then investigated the significance of an I3C-enhanced diet in ameliorating *C. tyzzeri* infection in a mouse model that recapitulates early childhood infection in humans. Since AHR is known to be important in pregnancy (Hernandez-Ochoa et al., 2009), we changed the diet of WT dams that had just given birth from normal chow to either a purified control diet or an I3C-enriched diet. 3 weeks

later, pups were weaned on the same diet that their mothers had received and infected with *Ct*-CR (**Figure 6F**). WT pups that grew up on the purified control diet were far more susceptible to infection than WT pups that grew up on the I3C diet (**Figure 6G**). Thus, prior exposure to I3C protects mice from *Cryptosporidium* infection.

Taken together, these data underscore the potential of dietary AHR ligands to modulate cytotoxic immune defence against *C. tyzzeri*, leading to improved elimination of infected epithelial cells, and thus offering a therapeutic avenue to prevent or treat cryptosporidiosis by enhancing immunity to *Cryptosporidium* through dietary interventions.

DISCUSSION

While ubiquitously prevalent, *Cryptosporidium* is particularly problematic in resource-poor settings. Malnutrition is endemic to those same settings, which is in turn a risk factor for *Cryptosporidium* infections and chronic diarrhoea (Iannotti 2015). Malnutrition and immunodeficiency increase the risk of recurrent *Cryptosporidium* infections, which contributes to increased morbidity and mortality (Checkley et al., 2015). The findings presented in this study using a mouse model of infection offers a proof of concept for the potential use of dietary AHR ligands such as I3C to curb this vicious cycle of chronic infections, diarrhoea, and malnutrition in humans and farm animals. Many resource-poor regions across the world already rely on ready-made food formulations such as RUTF (Ready-to-Use Therapeutic Food) to treat children suffering from severe wastage and malnutrition, often as the result of infections, with varying degrees of success (Schoonees et al., 2019). Several human clinical trials show that I3C is safe for human consumption in adults (Naik et al., 2006; Reed et al., 2005; Wong et al., 1997). I3C supplements are commercially available on the market and thus it is conceivable for them to be included in RUTF formulations following controlled human challenge trials confirming their therapeutic potential. Intriguingly, it has

also been shown that nursing mice can pass on AHR ligands to their newborn (Lu 2021). Therefore, there is also scope for dietary prophylactic interventions to be made at the level of nursing mothers, especially since *Cryptosporidium* infections are most severe in children less than one year old.

In laboratory settings, younger mice are also more susceptible to *Cryptosporidium* infections. Here, we have shown the importance of cytotoxic $CD8^+$ IELs in controlling this infection in an AHR-dependent manner. Due to their close association with intestinal epithelial cells, IELs are known to be primary responders to several invading pathogens in the gut (Edelblum et al., 2015; Hoytema van Konijnenburg et al., 2017; Ismail et al., 2011) and our findings support these observations in the context of *Cryptosporidium* infection. $CD8^+$ IELs (natural CD8αα and induced CD8αβ) in the gut are long-lived tissue-resident memory cells. Natural CD8αα cells populate the relatively abiotic guts of pups in response to self-antigens during weaning (Ruscher et al., 2020), while CD8αβ IELs accumulate over time in response to externally-derived antigens (Cheroutre et al., 2011). While the exact mechanism by which these IELs sense epithelial injury during infection is unclear (Hoytema van Konijnenburg et al., 2017), being in a constant state of heightened activation with increased cytolytic granzyme expression (Konjar et al., 2018) increases their ability to swiftly act on *Cryptosporidium*-infected epithelial cells. The presence of IELs at the coalface of the mucosal barrier and their dependence on AHR (Dean et al., 2023; Li et al., 2011; Panda et al., 2023), opens up the possibility to modulate these IELs during *Cryptosporidium* infections through supplementation of dietary AHR ligands.

IFNγ is a key cytokine responsible for early protection from *C. tyzzeri* infection (Gullicksrud et al., 2022; Sateriale et al., 2019). Interestingly, natural CD8αα IELs do not produce as much

IFNγ as their induced CD8αβ counterparts although both robustly respond to *C. tyzzeri* infection. However, both TCRαβ$^+$ and TCRγδ$^+$ IELs expressed cytotoxic granular protein granzyme-B in their quiescent and activated states. A heightened state of activation with increased cytotoxic potential and rapid proliferative capacity could facilitate swift killing of *C. tyzzeri*-infected epithelial cells by IELs. Indeed, AHR deficient mice (AHRKO^{Body} and AHRKO^{Immune}) that lack these IELs have elevated parasite burdens from DPI-2 onwards, suggesting that in the absence of cytotoxic CD8$^+$ IELs *C. tyzzeri* robustly establish an infection in the small intestine. In contrast to CD8αα IELs, induced CD8αβ IELs can form antigen-specific long-lived memory cells (Soerens et al., 2023). Future studies should explore the antigen-specificity of conventional TCRαβ$^+$CD8αβ IELs during primary and secondary infections and narrow down their role in long-term protection against subsequent *Cryptosporidium* infections.

We have previously established *C. tyzzeri* as a model of *Cryptosporidium* infection to study the relationships between a pathogen and its natural host (Sateriale 2019). Initial work showed parasite infections caused characteristic villus blunting, a decrease in villus-crypt height ratios, as well as an increase in mitotic events in the epithelium of the small intestine. Here, we further characterised the pathological effects of the *C. tyzzeri*-CR strain on the mouse small intestine and found that it produces many hallmarks of epithelial damage. There is increased expression of IFNγ at the tissue level, a loss of markers of differentiated cells such as ChgA and Dclk1, as well as an increase in the enterocyte marker Car4. Most notably, Sca-1 protein levels significantly increased in infected epithelial tissue, a notable marker of epithelial damage previously seen in mouse models of colitis (Shah et al., 2022; Yui et al., 2018). Increased Sca-1 expression is also caused during infection by the intestinal parasitic helminth *H. polygyrus* in an IFNγ-dependent manner and is indicative of a reversion to a fetal-

like state in tissue (Nusse et al., 2018) . We hope that this study paves the way for future work understanding how this parasite specifically damages the small intestine, potentially triggering a re-wiring of the epithelial regenerative response.

Taken together, we have further uncovered host responses to *C. tyzzeri* and revealed the role of environmental sensor AHR and its natural ligands in conferring protection from *Cryptosporidium* infection by modulating gut-resident cytotoxic lymphocytes using a well-defined genetically tractable mouse model. This study extends our understanding of AHR signalling and its importance in maintaining gut barrier integrity in the small intestine and suggests a way forward towards future therapeutic strategies to control the severity of *Cryptosporidium* infections.

CONTACT FOR REAGENT AND RESOURCE SHARING

For further information and access to parasites, reagents and mice used in the study please address the lead contacts: Adam Sateriale (adam.sateriale@crick.ac.uk) and Brigitta Stockinger (brigitta.stockinger@crick.ac.uk)

EXPERIMENTAL METHOD DETAILS

Mouse model of infection:

Mice used in this study including C57BL/6, AHR deficient (AHRKO^{Body}), AHRf/f, Villin-Cre, Vav-Cre, CDH5-CreERT2, Rag2 knockout, and Rag2-IL-2rγ-CD47 knockout mice were bred in the Francis Crick Institute animal facility under specific pathogen free conditions. Experiments were conducted as per the guidelines detailed in the Project Licence granted by the UK Home Office. Both male and female mice aged between 3-6 weeks old were randomly assigned to experimental groups. For infection experiments, 50,000 *Ct*-CR oocysts were administered to each mouse by oral gavage. Parasite burden is measured in the feces and intestinal tissues.

Genome sequencing and alignment:

Genomic DNA was isolated from 2x10^7 C. tyzzeri sporozoites using a Qiagen DNeasy Blood & Tissue Kit. A DNA library was prepared with a Nextera XT DNA Library Preparation Kit (Illumina) and 150bp paired end reads were obtained on a MiSeq patform (Illumina). To align the reads, the refence genome for C. tyzzeri (UGA55) was first downloaded from CryptoDB (Amos et al., 2022). Reads were aligned using Burrows-Wheeler Aligner (bwa mem) and converted into bam format using Samtools (Li and Durbin, 2009). Duplicate reads were then removed and reindexed GATK. Variants were called with GATK HaplotypeCaller using a ploidy of 1 (*Cryptosporidium* sporozoites are haploid) (McKenna et al., 2010). Variants were finally annotated with SnpEff (Cingolani et al., 2012) and plotted against the reference genome using circlize package for R (Gu et al., 2014).

Generation of transgenic parasites

Transgenic *C. tyzzeri*-CR parasites were created using methods described previously (Pawlowic et al., 2017; Sateriale et al., 2020). Briefly, 1.5 x 10^6 oocysts were bleach-treated and incubated at 37 ^oC in 0.75 % sodium taurocholate for one hour to promote excystation. Sporozoites were transfected with a plasmid expressing Cas9 and guide targeting the *C. tyzzeri* TK gene, along with a repair template carrying Nanoluciferase, mNeonGreen, and neomycin resistance genes. IFN$\gamma^{-/-}$ mice were orally gavaged with these transfected sporozoites, following a sodium bicarbonate oral gavage a few minutes prior. Mice were given Paromomycin in their drinking water to select for transgenic parasites and Nanoluciferase levels in fecal samples were tracked over time.

Measuring parasite burden in tissues and feces

Nanoluciferase readings from fecal samples were performed as a proxy for parasite burdens as previously described using the NanoGlo Luciferase reporter assay (NanoGlo kit, Promega, N1150) (Vinayak et al., 2015). Small intestinal tissue sections were cut, weighed, and processed in a similar manner to fecal samples.

Isolation of parasites

Parasites were isolated from daily mouse fecal collections by sucrose flotation followed by cesium chloride-mediated density gradient centrifugation as described previously (Pawlowic et al., 2017). Briefly, 5-7 days' worth of fecal samples were made into a slurry in tap water and filtered through a sieve of 250 um pore size. Filtrates were mixed 1:1 in a sucrose solution (1.33 specific gravity) and centrifuged at 1000 g at 4 ^oC. The supernatant was washed in cold water (1:100), centrifuged again at 1500 g at 4 ^oC and resuspended in cold saline. This suspension was carefully laid over a cesium chloride solution (1.25 M) in a 1:1 ratio and

centrifuged at 16,000 g at 4 ^{o}C to produce an interphase containing suspended oocysts. These were collected and stored in cold saline for future use.

Isolation and transfer of intraepithelial lymphocytes

IELs were isolated from the small intestine. Small intestine was cut open longitudinally and washed twice in Ca^{2+} and Mg-free PBS to remove the intestinal contents. Cleaned intestine was cut into 1cm pieces and resuspended with HBSS (Ca^{2+} and Mg-free) containing 5% FCS and 2mM EDTA. Tissue pieces were incubated for 30 minutes at 37°C with shaking at 200 r.p.m. Single cell suspension from the epithelial wash was resuspended in 36% Percoll (Amersham) and layered on top of 67% Percoll (Amersham; Cat# 17-0891-01) and subjected to density gradient centrifugation at room temperature (700g for 30 minutes). Intermediate layer containing IELs was collected and washed with 1X PBS followed by either flowcytometry analysis or used for CD8α IELs purification using EasySep™ mouse CD8a positive selection kit-II (StemCell Technologies; Cat# 18953). Sort purified CD8α IELs (50,000/mouse) were intravenously injected into recipient Rag2-IL-2rγ-CD47 knockout mice.

For measurement of intracellular IFNγ ex-vivo harvested IELs were restimulated with PMA (20ng/ml final concentration) and ionomycin (1μM final concentration) in the presence of brefeldin-A (10μg/ml final concentration) for 3 hours. In some experiments, epithelial cells (top layer of 36% Percoll gradient) that were separated from IELs was used for RNA extraction.

Flow cytometry

Single cell suspension was first stained with LIVE/DEAD Near-IR dead cell stain (Invitrogen; Cat# L10119). Cell suspensions were then incubated with surface staining antibodies targeting CD45 (Cat# 103146; Clone: 30-F11), CD103 (Cat# 12-1031-82; Clone: 2E7), TCRβ (Cat# 109224; Clone:H57-597), TCRγδ (Cat# 118123 & Cat# 118106; Clone:GL3), CD4 (Cat# 100557; Clone: RM4-5), CD8α (Cat# 100734; Clone:53.6-7), CD8β (Cat# 740952; Clone: H35-17.2). For

intracellular protein staining, cells were fixed and permeabilized using eBioscience FOXP3 staining kit (Invitrogen; Cat# 00-5523-00) followed by intracellular staining of Ki67 (eBiosciences; Cat# 17-5698-82; Clone:SOIA15), Granzyme-B (Biolegend; Cat# 515408; Clone:GB11) and IFNγ (BD Biosciences; Cat# 557724; Clone: XMG1.2) as per the experimental condition. Acquired data was analysed using Flowjo software (https://www.flowjo.com/). Identification of different subsets of IELs was described in the Figure S1.

Immunohistochemistry and Immunofluorescence Staining:

Mouse ileal sections were fixed in 4 % PFA for at least 4 hours and then treated in a solution of 10 % glycerol and 25 % sucrose prior to embedding in OCT. Sections were stained with anti-CD3-AF488 (1: 200; Cat# 100210; Clone: 17A2), Phalloidin-647 (1:1000; Cat# A22287, ThermoFisher), and DAPI (1:1000; Sigma; Cat# D9542). Some sections were stained with Sca-1 (1: 200; Cat# 122501; Clone:E13-161.7.) Images were taken with a laser scanning confocal microscope (Zeiss LSM 880) and processed using FIJI (ImageJ version 2.1.0/1.53c).

Bioimage analysis of Sca-1 immunofluorescence Staining:

OCT embedded cryosections were stained with Sca-1 as mentioned above. Quantification of Sca-1+ areas in the small intestinal epithelium was performed blindly using QuPath software (Bankhead et al., 2017). The epithelial layer of the villi in the small intestine was delineated manually using the polygon or brush tool in QuPath. 6 villi per small intestine were analyzed. Using the automated quantification tool, mean fluorescence intensity per area unit was estimated. This was repeated in sections stained without primary antibody as controls. The average fluorescence intensity values from the control sections were subtracted from the fluorescence intensity values obtained from each villi in the original samples. The fluorescence intensity values from 6 villi per small intestine were averaged, to report the mean GFP intensity per mouse.

Quantitative Real-time Polymerase Chain Reaction:

RNA from the gut tissues and epithelial cells was extracted using TRIzol RNA purification kit (Invitrogen; Cat# 9738G). cDNA was synthesized with high-Capacity cDNA Reverse Transcription Kit (Thermofisher; Cat# 4368814) and qRT-PCR was performed using Taqman 2X universal PCR master mix (Thermofisher; Cat# 4318157) with appropriate primer sets. Data was normalized to housekeeping genes HPRT or B2M.

Dietary intervention:

For dietary intervention studies mice were fed with synthetic purified control diet (AIN93M) (ssniff; Cat# E15713-047) or AIN93M diet supplemented with indole-3-carbinol (I3C) (1000mg/kg) (ssniff; Cat# S9477-E724) *ad libitum*.

Oligonucleotides:

Gene	Provider	Catalogue Number
IFNγ	TaqMan™ Assays	Cat# Mm01168134_m1
Olfm4	TaqMan™ Assays	Cat# Mm01320260_m1
Clu	TaqMan™ Assays	Cat# Mm01197004_m1
Sox9	TaqMan™ Assays	Cat# Mm00448840_m1
Chga	TaqMan™ Assays	Cat# Mm00514341_m1
Dclk1	TaqMan™ Assays	Cat# Mm00444950_m1
Muc2	TaqMan™ Assays	Cat# Mm01276696_m1
Car4	TaqMan™ Assays	Cat# Mm00483021_m1
HPRT	TaqMan™ Assays	Cat# Mm00446968_m1
B2M	TaqMan™ Assays	Cat# Mm00437762_m1

Statistical analysis:

All statistical analysis was performed with GraphPad Prism software (version 9) (https://www.graphpad.com/). For comparison of 2 groups unpaired Student's *t*-test was used and for multiple comparison analyses a one-way ANOVA followed by Tukey's multiple comparison test was performed. $P < 0.05$ was considered as significant. Error bars represent

mean with standard error mean (SEM). ns-not significant, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, ****$p < 0.0001$.

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Figure 1: *Cryptosporidium tyzzeri* specifically infects the ileum and alters epithelial cell differentiation. (A) Chromosome-based Circos plot mapping the newly-sequenced *C. tyzzeri*-CR to the *C. tyzzeri*-UGA55 strain. Tracks from the outside-in are mean genome coverage per kb (grey), single-nucleotide polymorphism (SNP) density per kb (blue), insertions density per kb (orange), and deletions density per kb (green). (B) Schematic of the cloning strategy for the introduction of genes expressing mNeonGreen, Nanoluciferase (NLuc), and Neomycin phosphotransferase (Neo^R) by Cas9-directed homology repair of the *C. tyzzeri*-CR Thymidine Kinase gene. (C) Immunofluorescence image showing mNeonGreen-expressing parasites in the intestinal villi from the ileal section of an immunocompromised mouse. (D) *C. tyzzeri* (*Ct*-CR) parasite burden in the feces measured by Nanoluciferase assay. (E) Regional-specific *Ct*-CR parasite burden in infected wild type (WT) mice. (F) *Ct*-CR burden in the duodenum, jejunum and ileum (G) Fecal levels of *Ct*-CR in infected WT mice. (H) qPCR of IFNγ in ileum tissue. (I) Sca-1 expressing epithelial cells in uninfected and *Ct*-CR infected WT mice. (J-N) qPCR of purified epithelial cells for marker genes of stemness (Olfm4, Clu, Sox9) (J) and differentiated epithelial cells (K-N). (F-H) N=4 per time point (E, I-N) Representative of at least 2 independent experiments. Each dot represents individual mice. Error bars, mean + SEM. ns-not significant, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, ****$p < 0.0001$ as calculated by t-test or one- way ANOVA with Tukey post-test.

Figure 2: Hematopoietic cell-specific AHR signalling is indispensable to control *C. tyzzeri* infection. (A) *Ct*-CR parasite burden (left panel) and the area under the curve (AUC) (right panel) in WT and total body AHR knockout mice. (B) AHR-tdTomato expression in intestinal epithelial cells. (C) *Ct*-CR parasite growth in WT ($Villin^{Cre}$ AHR^{WT}) and epithelium-specific AHR knockout mice ($Villin^{Cre}$ $AHR^{f/f}$). (D) AHR-tdTomato expression in small intestinal immune cells (CD45+) (E) *Ct*-CR parasite growth in WT (Vav^{Cre} AHR^{WT}) and immune cell-specific AHR

knockout mice (Vav^{Cre} AHR$^{f/f}$). (F) Area under the curve of *Ct*-CR growth in endothelial (Cdh5^{Cre} AHR$^{f/f}$) and immune cell-specific AHR knockout mice (Vav^{Cre} AHR$^{f/f}$). (G) *Ct*-CR burden at the peak of infection (DPI-6) in total-body and immune cell-specific AHR knockout mice. (H) qPCR of marker genes of enterocytes (Car4), stem cells (Olfm4) and tuft cells (Dclk1). (A-I) Representative results of at least 2 independent experiments. Each dot represents individual mice. Error bars, mean + SEM. ns-not significant, *p < 0.05, **p < 0.01, ****p < 0.0001 as calculated by t-test or one-way ANOVA with Tukey post-test.

Figure 3: AHR-expressing CD8α intraepithelial lymphocytes respond to *C. tyzzeri* parasite infection (A) Representative image showing *Ct*-CR (yellow arrow-head pointing to mNeonGreen positive parasites on the luminal side of villi) and the close proximity of intraepithelial lymphocytes (magenta arrow pointing to CD3$^+$ IELs) to infected epithelial cells in the ileum. (B) AHR-tdTomato expression by TCRαβ and TCRγδ CD8$^+$ IEL subsets. (C&D) Ki67+ proliferating IELs in the *Ct*-CR infected WT mice. (E) Number of IELs in the small intestine of *Ct*-CR infected WT mice. (F) Intracellular IFNγ levels of TCRαβ and TCRγδ CD8$^+$ IEL subsets. (G) Histogram of intracellular granzyme-B in TCRαβ and TCRγδ CD8$^+$ IEL subsets. (A-G) Representative results of at least 2 independent experiments. Each dot represents individual mice. Error bars, mean + SEM. *p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.0001 as calculated by t-test or one-way ANOVA with Tukey post-test.

Figure 4: AHR expression influences the CD8α IEL response to *C. tyzzeri* infection. (A) Representative flow cytometry plots showing the percentage of CD8α IEL subsets in WT and AHRKO^{Immune} mice at steady state. (B & C) Percentage (B) and absolute number (C) of TCRαβ and TCRγδ CD8$^+$ IEL subsets in AHRKO^{Immune} mice and littermate WT controls at steady state. (D & E) Percentage (D) and absolute number (E) of CD8$^+$ IEL subsets on day 7 post-*Ct*-CR infection (C). (D & E) Representative FACS plots (F) and percentage (G) of Ki67 positive CD8α

IEL subsets in *Ct*-CR-infected mice. (H) Percentage of granzyme-B-expressing total $CD8^+$ IELs (I) Mean fluorescence intensity (MFI) of intracellular granzyme-B in TCRαβ and TCRγδ $CD8^+$ IEL subsets in $AHRKO^{Immune}$ mice and littermate WT controls infected with *Ct*-CR. (A-G) Representative results of at least 2 independent experiments. Each dot represents individual mice. Error bars, mean + SEM. ns- not significant, *p < 0.05, **p < 0.01, ***p < 0.001, as calculated by t-test.

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Table S1: Summary of genome comparisons between *C. tyzzeri* strain UGA55 and *C. tyzzeri* strain CR2206.

	SNPs		INDELs
Coding regions	Synonymous	Non-synonymous	2464
	3773	5014	
Non-coding regions	4315		518

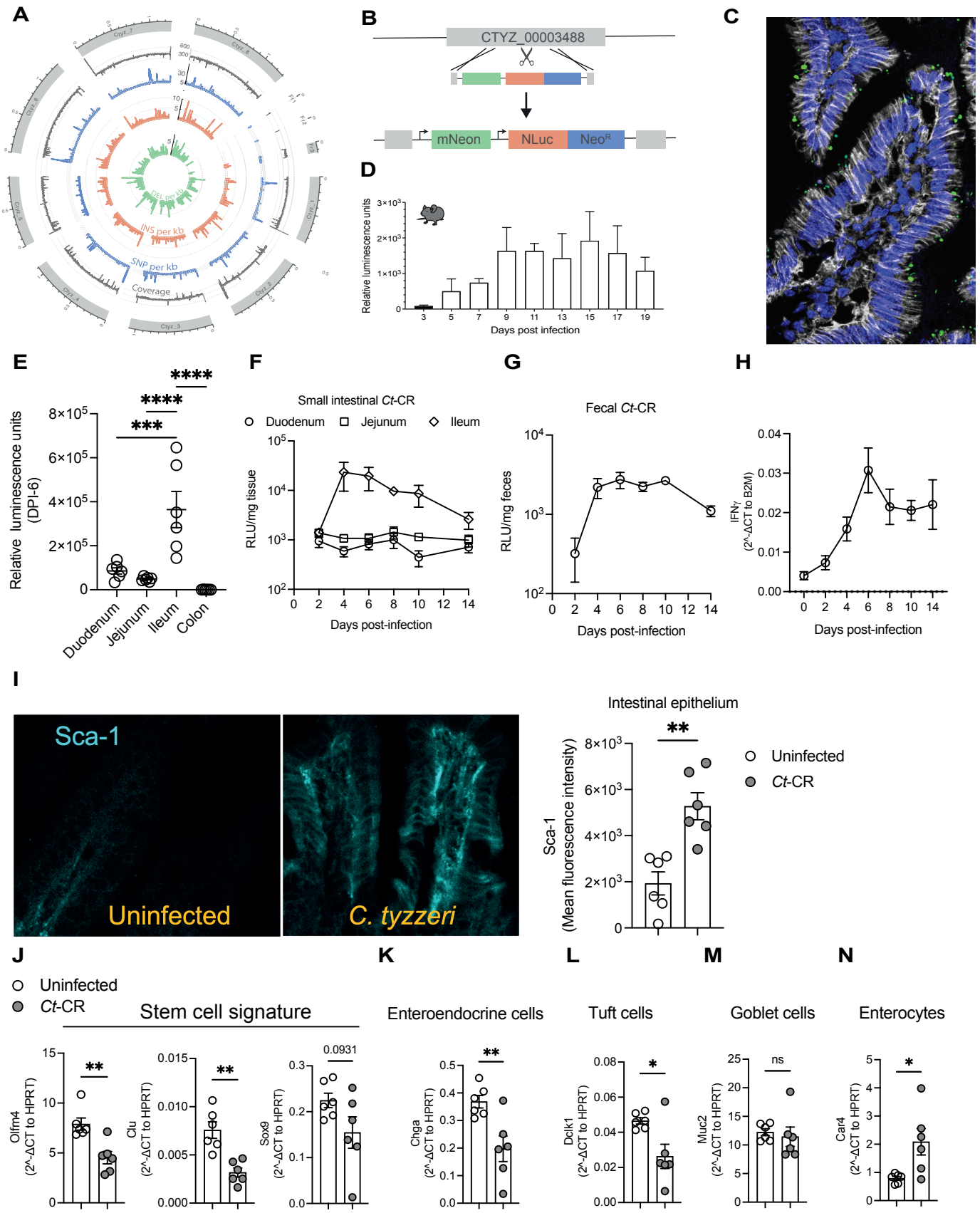


Figure 1: Cryptosporidium tyzzeri specifically infects the ileum and alters epithelial cell differentiation. (A) Chromosome-based Circos plot mapping the newly-sequenced C. tyzzeri-CR to the C. tyzzeri-UGA55 strain. Tracks from the outside-in are mean genome coverage per kb (grey), single-nucleotide polymorphism (SNP) density per kb (blue), insertions density per kb (orange), and deletions density per kb (green). (B) Schematic of the cloning strategy for the introduction of genes expressing mNeonGreen, Nanoluciferase (NLuc), and Neomycin phosphotransferase (NeoR) by Cas9-directed homology repair of the C. tyzzeri-CR Thymidine Kinase gene. (C) Immunofluorescence image showing mNeonGreen-expressing parasites in the intestinal villi from the ileal section of an immunocompromised mouse. (D) C. tyzzeri (Ct-CR) parasite burden in the feces measured by Nanoluciferase assay. (E) Regional-specific Ct-CR parasite burden in infected wild type (WT) mice. (F) Ct-CR burden in the duodenum, jejunum and ileum (G) Fecal levels of Ct-CR in infected WT mice. (H) qPCR of IFNγ in ileum tissue. (I) Sca-1 expressing epithelial cells in uninfected and Ct-CR infected WT mice. (J-N) qPCR of purified epithelial cells for marker genes of stemness (Olfm4, Clu, Sox9) (J) and differentiated epithelial cells (K-N). (F-H) N=4 per time point (E, I-N) Representative of at least 2 independent experiments. Each dot represents individual mice. Error bars, mean + SEM. ns-not significant, *p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.0001 as calculated by t-test or one- way ANOVA with Tukey post-test.

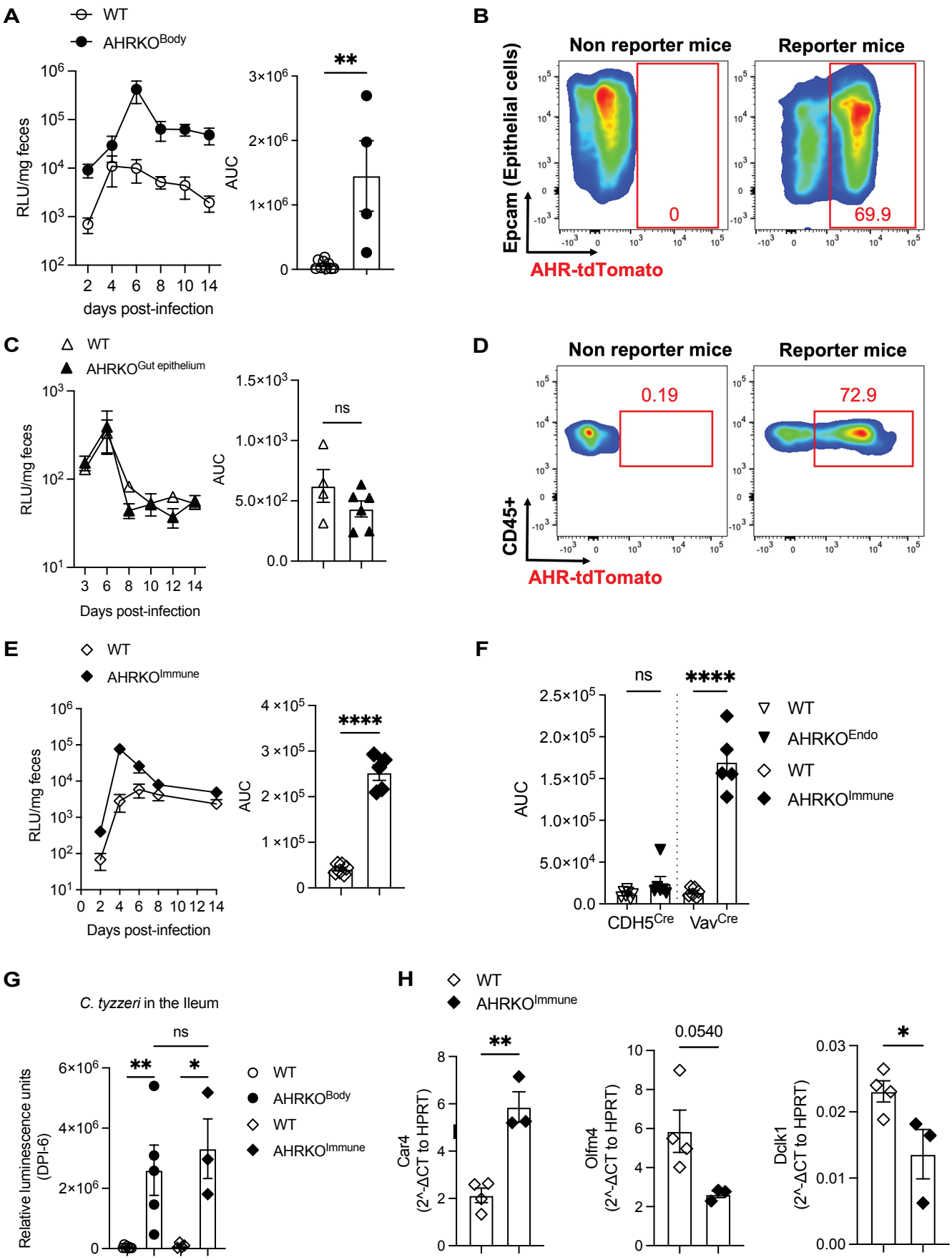


Figure 2: Hematopoietic cell-specific AHR signalling is indispensable to control C. tyzzeri infection. (A) Ct-CR parasite burden (left panel) and the area under the curve (AUC) (right panel) in WT and total body AHR knockout mice. (B) AHR-tdTomato expression in intestinal epithelial cells. (C) Ct-CR parasite growth in WT (Villin^{Cre} AHR^{WT}) and epithelium-specific AHR knockout mice (Villin^{Cre} AHR$^{f/f}$). (D) AHR-tdTomato expression in small intestinal immune cells (CD45^{+}) (E) Ct-CR parasite growth in WT (Vav^{Cre} AHR^{WT}) and immune cell-specific AHR knockout mice (Vav^{Cre} AHR$^{f/f}$). (F) Area under the curve of Ct-CR growth in endothelial (Cdh5^{Cre} AHR$^{f/f}$) and immune cell-specific AHR knockout mice (Vav^{Cre} AHR$^{f/f}$). (G) Ct-CR burden at the peak of infection (DPI-6) in total-body and immune cell-specific AHR knockout mice. (H) qPCR of marker genes of enterocytes (Car4), stem cells (Olfm4) and tuft cells (Dclk1). (A-I) Representative results of at least 2 independent experiments. Each dot represents individual mice. Error bars, mean + SEM. ns-not significant, *$p < 0.05$, **$p < 0.01$, ****$p < 0.0001$ as calculated by t-test or one-way ANOVA with Tukey post-test.

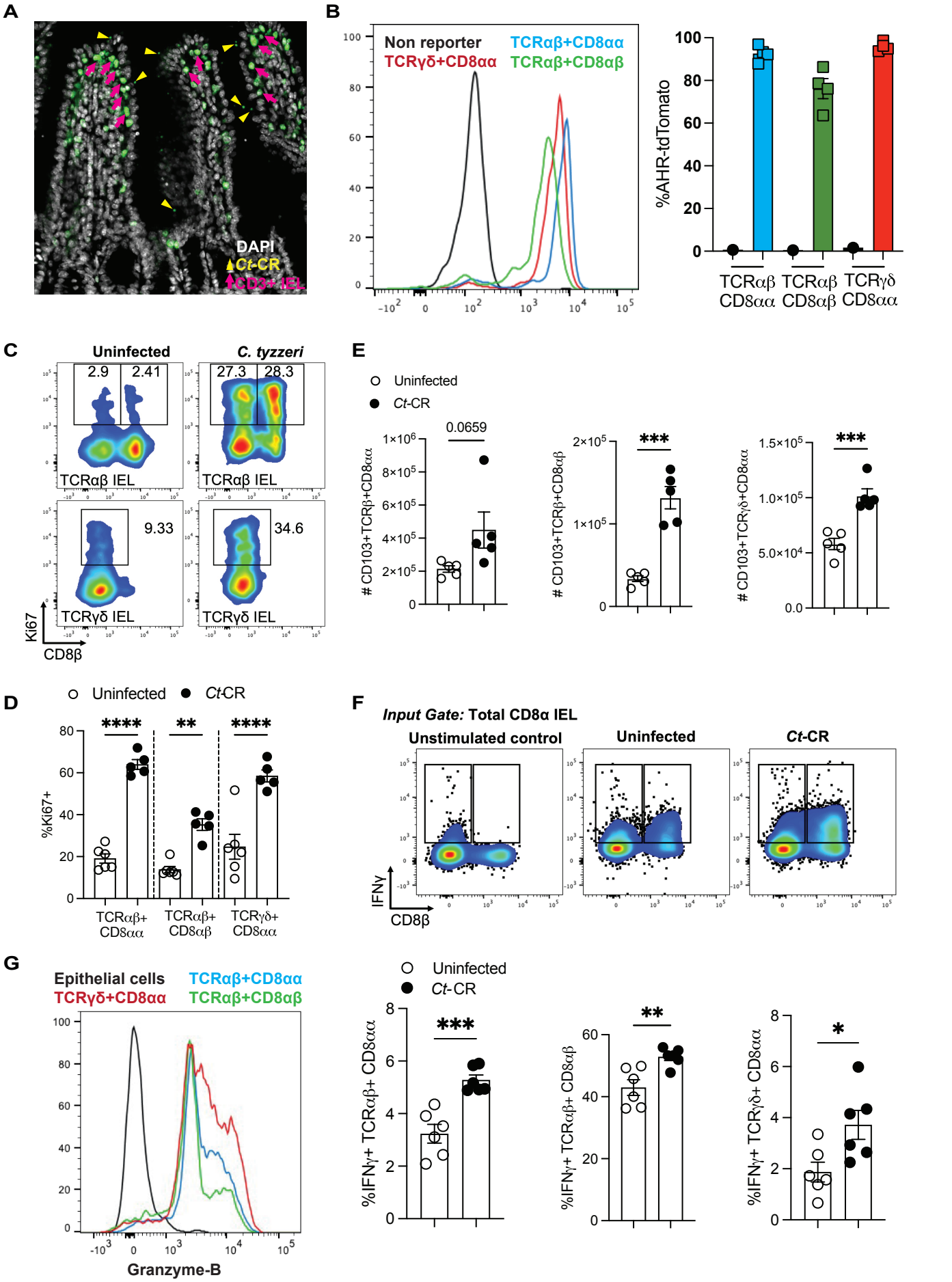
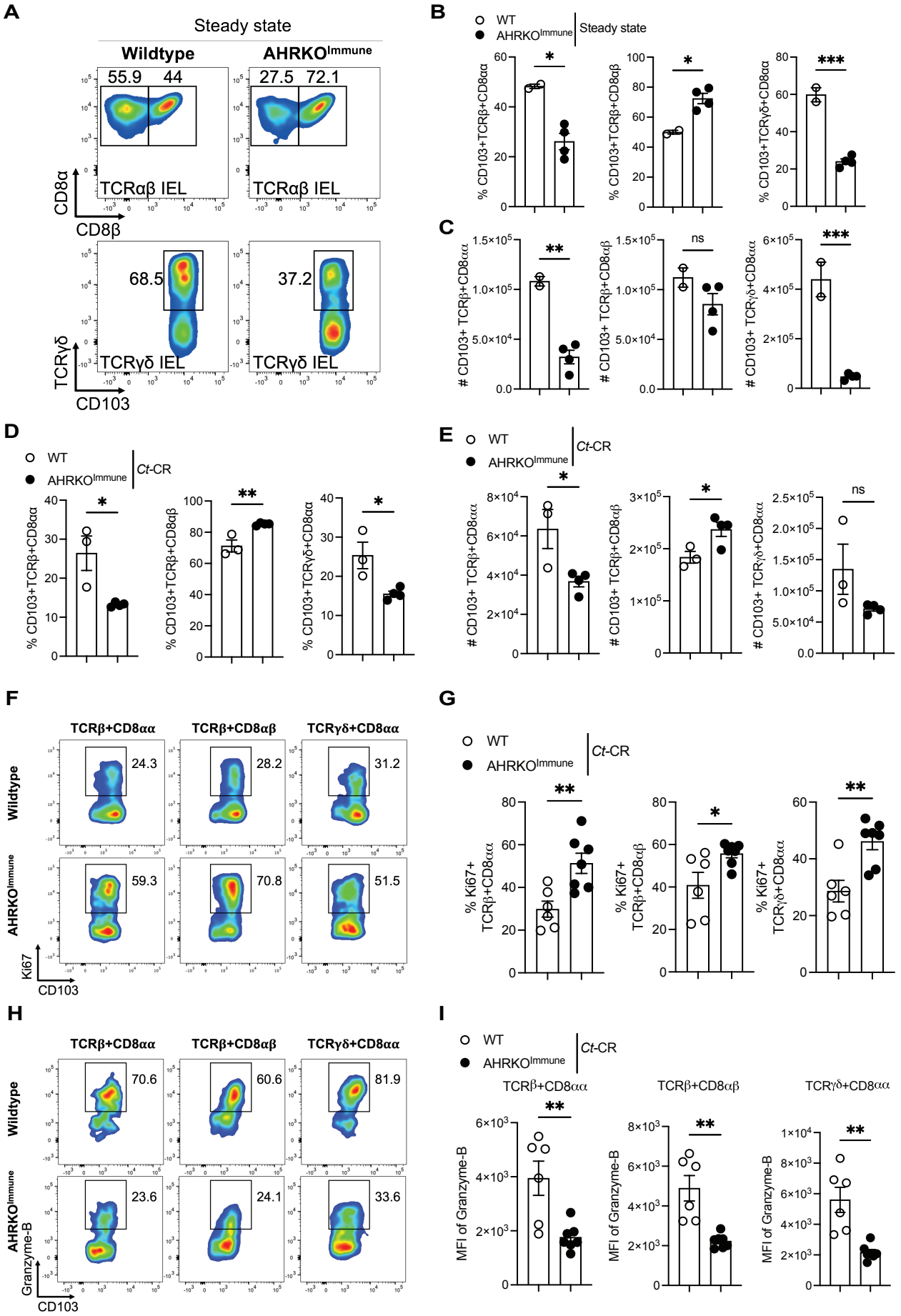


Figure 3: AHR-expressing CD8α intraepithelial lymphocytes respond to C. tyzzeri parasite infection. (A) Representative image showing Ct-CR (yellow arrow-head pointing to mNeonGreen positive parasites on the luminal side of villi) and the close proximity of intraepithelial lymphocytes (magenta arrow pointing to CD3⁺ IELs) to infected epithelial cells in the ileum. (B) AHR-tdTomato expression by TCRαβ and TCRγδ CD8+ IEL subsets. (C&D) Ki67⁺ proliferating IELs in the Ct-CR infected WT mice. (E) Number of IELs in the small intestine of Ct-CR infected WT mice. (F) Intracellular IFNγ levels of TCRαβ and TCRγδ CD8⁺ IEL subsets. (G) Histogram of intracellular granzyme-B in TCRαβ and TCRγδ CD8⁺ IEL subsets. (A-G) Representative results of at least 2 independent experiments. Each dot represents individual mice. Error bars, mean + SEM. *p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.0001 as calculated by t-test or one-way ANOVA with Tukey post-test.



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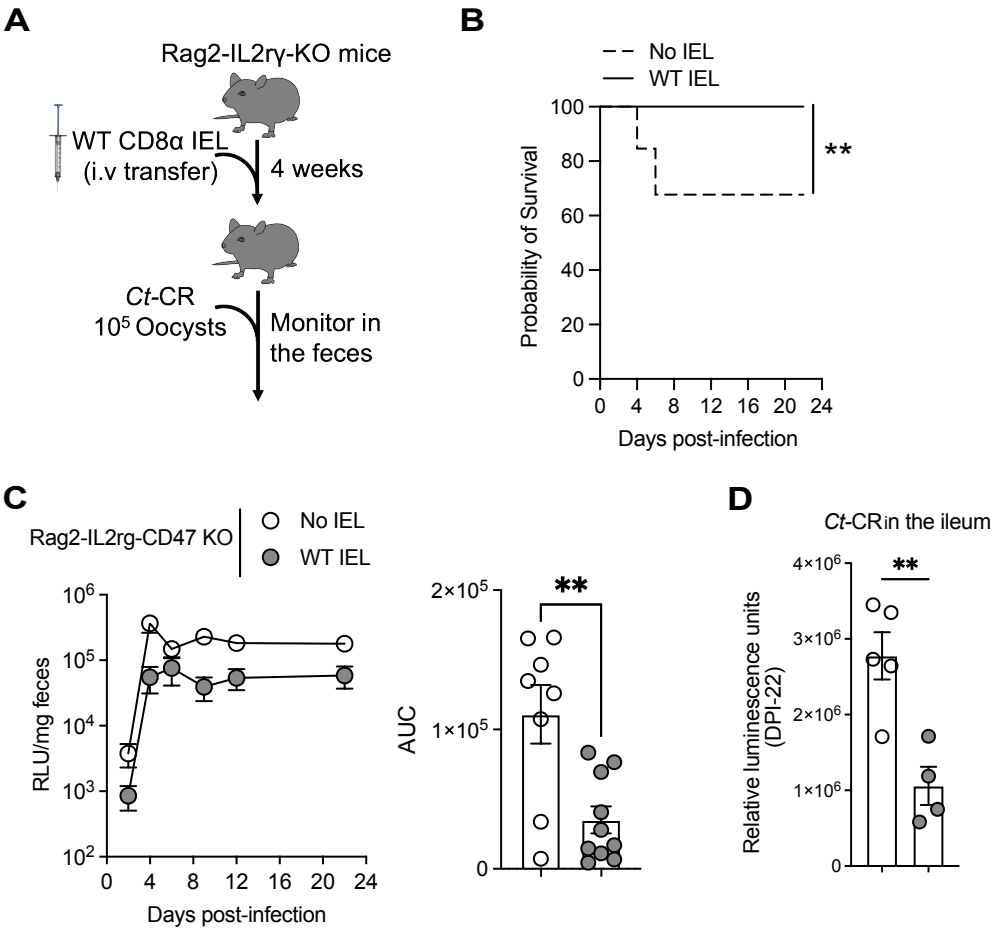

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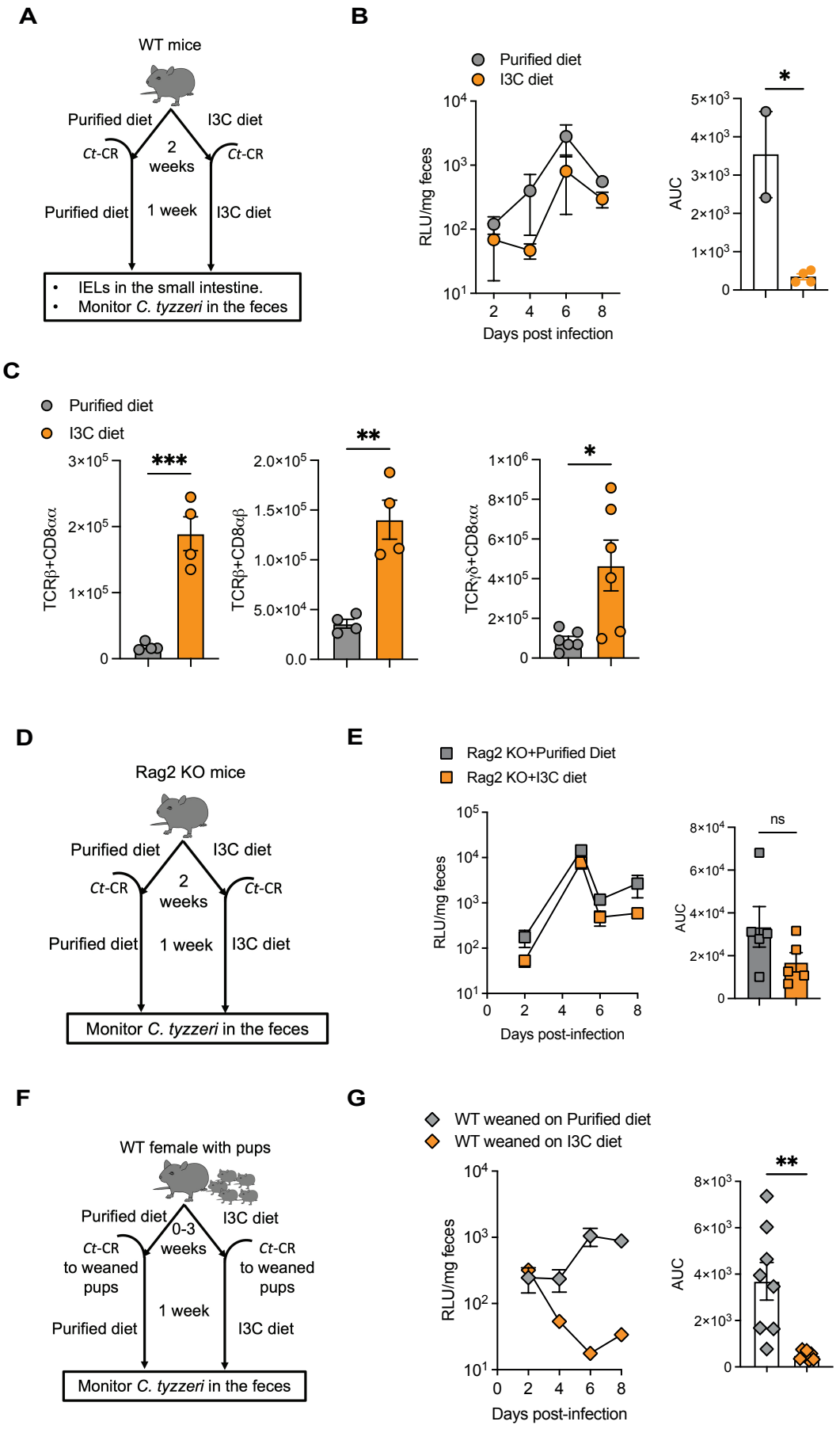

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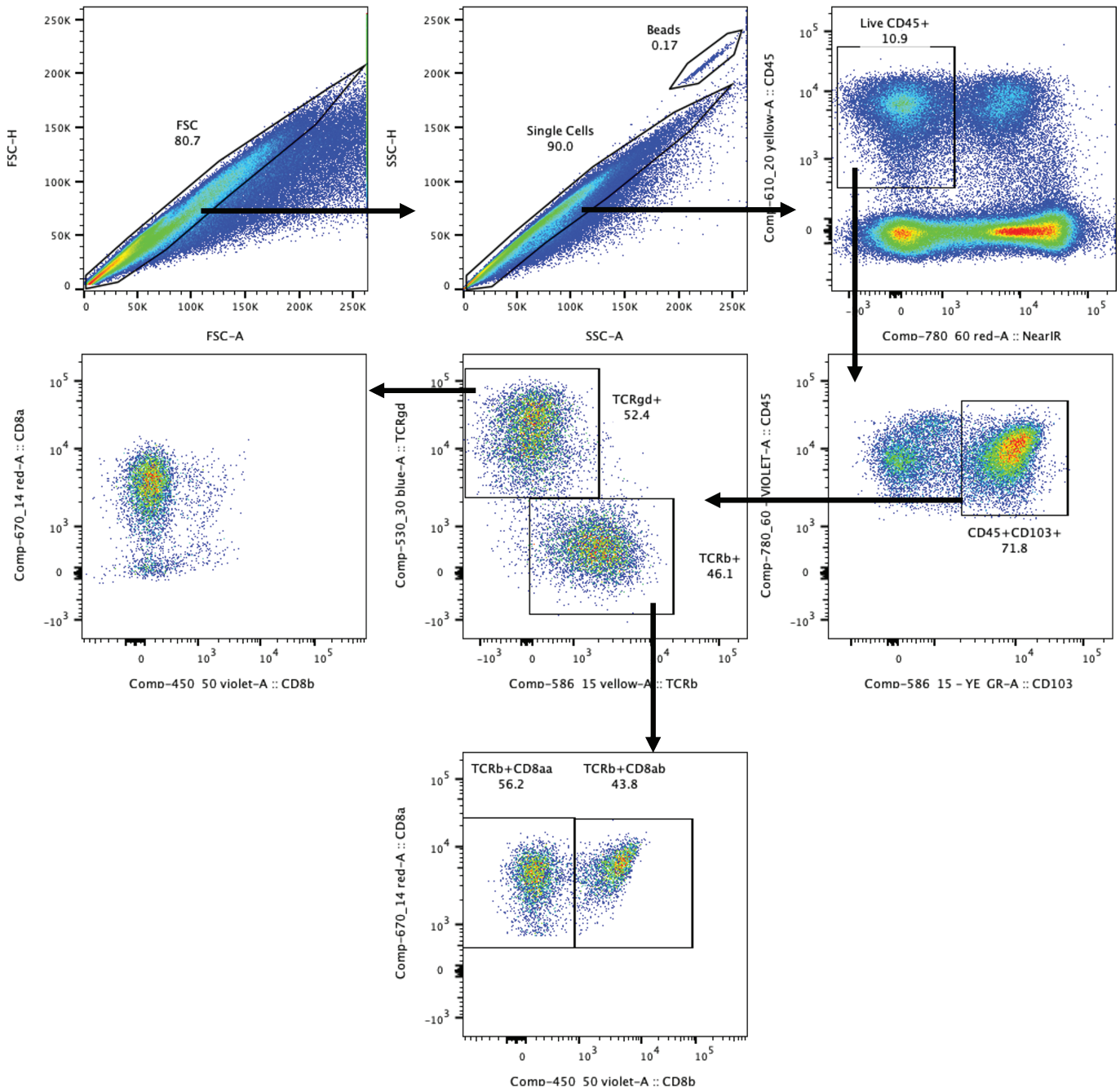

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