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Tuberculosis alters immune-metabolic pathways resulting in perturbed IL-1 responses

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Tuberculosis (TB) remains a major public health problem and we lack a comprehensive understanding of how *Mycobacterium tuberculosis* (*M. tb*) infection impacts host immune responses. We compared the induced immune response to TB antigen, BCG and IL-1 β stimulation between latently *M. tb* infected individuals (LTBI) and active TB patients. This revealed distinct responses between TB/LTBI at transcriptomic, proteomic and metabolomic levels. At baseline, we identified a novel immune-metabolic association between pregnane steroids, the PPAR γ pathway and elevated plasma IL-1ra in TB. We observed dysregulated IL-1 responses after BCG stimulation in TB patients, with elevated IL-1ra responses being explained by upstream TNF differences. Additionally, distinct secretion of IL-1 α /IL-1 β in LTBI/TB after BCG stimulation was associated with downstream differences in granzyme mediated cleavage. Finally, IL-1 β driven signalling was dramatically perturbed in TB disease but was completely restored after successful treatment. This study improves our knowledge of how immune responses are altered during TB disease, and may support the design of improved preventive and therapeutic tools, including host-directed strategies.

KEYWORDS

tuberculosis, IL-1ra, IL-1, immunometabolism, systems immunology

Introduction

As the leading cause of death by infection, tuberculosis (TB) is a major global public health problem (1). It is estimated that one fourth of the world's population is infected by its causative agent, *Mycobacterium tuberculosis* (*M.tb*). *M.tb* infection results in a diverse clinical spectrum, which includes asymptomatic latent infection (LTBI), incipient or subclinical stages, and active TB disease (TB), which occurs in 5-10% of infected persons (2, 3).

M.tb alters the host's ability to clear infection by targeting immune and metabolic pathways. Initial research in mice, later supported by human studies (4), demonstrated that interferon γ (IFN γ), tumour necrosis factor (TNF) and interleukin (IL)-1 β are essential cytokines for immune control of *M.tb* (5–8). Signalling through the IL-1 receptor can be regulated by binding of the IL-1 receptor antagonist (IL-1ra) (9). Levels of circulating IL-1ra are elevated in TB patients, and have been proposed as a potential biomarker for diagnosis of active disease or response to treatment (10). However, little is known about the underlying mechanisms that lead to higher IL-1ra concentrations in active TB disease. Metabolic reprogramming is also crucial for determining successful immune responses (11). Furthermore, immune-metabolic signatures associated with TB progression have previously been described (12, 13).

To better understand how these crucial cytokine pathways are perturbed in active TB disease, we applied a standardised immunomonitoring tool (14, 15) to compare induced immune responses between LTBI and TB patients at proteomic, transcriptomic, and metabolomic levels. Relevant stimuli that were used included *M.tb* antigens (TB Ag), Bacillus Calmette-Guérin (BCG), IL-1 β , and a Null control. This approach revealed multiple differences at the proteomic and transcriptomic levels between LTBI and TB patients. Integration of induced cytokine responses with baseline metabolic profiles helped to identify new immune-metabolic associations in TB patients (ie. elevated plasma IL-1ra and the PPAR γ pathway). After BCG stimulation, IL-1ra was secreted at higher levels in active TB patients compared to LTBI. Experimental analysis revealed that this correlated with differences in TNF mediated signalling. Furthermore, IL-1 α and IL-1 β were secreted at lower levels in active TB patients, probably due to differences in post-translational modifications. Finally, IL-1 β stimulation revealed a dysregulated IL-1 signalling response in TB patients, which was restored after successful treatment. Overall, our approach adds new understanding of how *M.tb* impacts human immune responses, providing new avenues for better diagnostic tools, vaccines and treatments, including host-directed therapeutics.

Results

Immune stimulation identifies specific gene expression differences that improve stratification of active TB disease from latent *M.tb* infection

To examine how TB disease perturbs immune responses, we stimulated whole blood from active TB patients and LTBI controls with relevant stimuli that included TB Ag, BCG and IL-1 β , plus a non-stimulated control (Null). Principal component analysis (PCA) of 622 immune genes measured showed clustering of stimuli-specific responses in both LTBI and TB, with 54% of the total variance captured by the first three principal components (Figure 1A and Supplementary Figure S1A). As previously reported (16), several genes were differentially expressed in active TB disease compared to LTBI in the absence of stimulation, namely 32% (200 genes, $q < 0.001$) of the immune genes examined.

Focusing on differential genes that were revealed only by immune stimulation, we compared LTBI and TB groups using a t-test with a stringent cut-off value of $q < 0.001$. This resulted in 114 genes (18% of total) with differences between LTBI and TB groups only after specific stimulation (TB Ag; 71, BCG; 28, IL-1 β ; 15) (Figure 1B and Supplementary Table S2), with TB Ag stimulation revealing significantly more differences than the other stimulations (Supplementary Table S3). Examples of stimuli-specific induced differences for each condition and the Null are illustrated in Figure 1C; Supplementary Figure S1B and Supplementary Table S4.

Whole blood transcriptomic approaches, based on signatures that primarily comprise interferon stimulated genes (ISG), are being developed for TB diagnosis, with promising strategies based on a 3-gene signature (Sweeney3 signature) in which a TB score is calculated using the formula $(GBP5 + DUSP3)/2 - KLF2$ (17), or the 11-gene blood TB risk signature, RISK11 (18). As TB Ag stimulation induced a high number of differences between LTBI and TB patients, we tested whether standardised immune stimulation could improve the performance of these signatures by comparing ROC curve analysis from Null and TB Ag stimulated samples (Figures 1D, E; Supplementary Figure S1D, S1E). For the Sweeney3 signature, TB Ag stimulation accentuated the pre-existing differences at baseline, which translated into a superior area under the receiver operating characteristic curve (AUC) for Null_{AUC} of 0.82 [95% CI (0.66–0.94)] and for TB Ag_{AUC} of 0.95 [95% CI (0.88–1)] improving the ability to classify LTBI and TB cases ($p = 0.02$) (Figure 1E). Similar results were obtained with the RISK11 signature, with Null_{AUC} of 0.82 [95% CI (0.69–0.94)] and TB Ag_{AUC} of 0.97 [95% CI (0.93–1)] ($p = 0.02$).

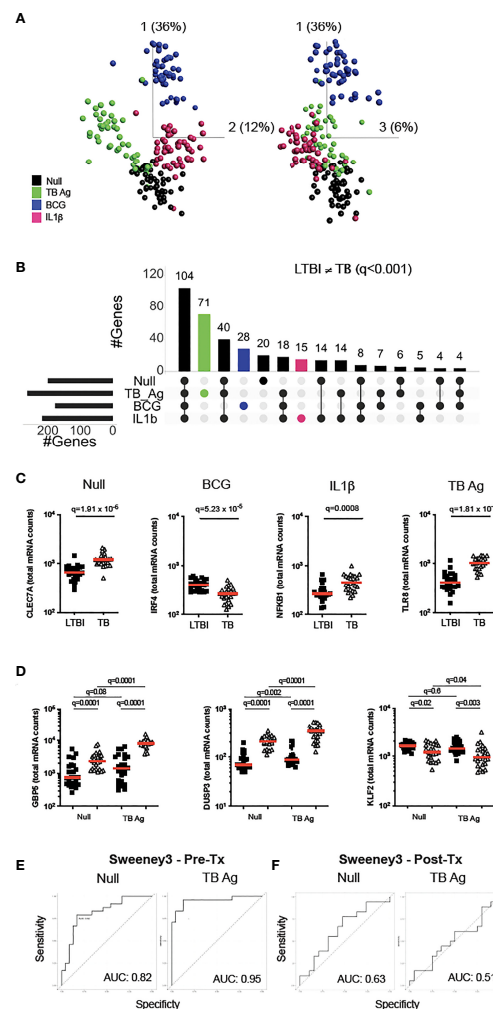


FIGURE 1

Immune stimulation identifies specific gene expression differences between latent *M.tb* infection and active TB disease. **(A)** Principal component analysis (PCA) on expression of 622 genes from 24 individuals with latent *M.tb* infection (LTBI) and 24 with active TB disease (TB) after whole blood stimulation with TB Ag, BCG, IL-1 β , and a non-stimulated control (Null). Each coloured circle represents one individual (LTBI or TB) for each condition. **(B)** Upset plot showing the intersection of differentially expressed genes (q value < 0.001, Mann-Whitney corrected for multiple comparisons) between TB and LTBI, across the four stimulations. Coloured bars depict the number of differentially expressed genes between LTBI and TB for each specific stimulation (TB Ag – green; BCG – blue; IL-1 β – pink). **(C)** Examples of significantly different stimuli-specific transcripts (q < 0.001) between TB and LTBI. **(D)** Expression of the 3 genes from the Sweeney TB score (Sweeney3) in the Null and TB Ag conditions on visit 1 pre-treatment. Area under the receiver operating characteristic curve (AUC) for discrimination of LTBI/TB groups using Sweeney3 for the Null and TB Ag conditions on visit 1 pre-treatment (Pre-Tx) **(E)** and on visit 2 after successful antibiotic treatment (Post-Tx) **(F)**. Comparisons of LTBI/TB groups within the same stimulation were performed using unpaired non-parametric t-tests; comparisons between Null and stimulated conditions within the LTBI/TB groups were performed using a paired non-parametric t-test. Correction for multiple comparisons was then applied. Red line: median values. Closed square: LTBI, Open triangle: TB. For panels **(C, D)**, q values (false discovery rate-adjusted p values) are reported.

(Supplementary Figure S1E). These differences were not present after successful antibiotic treatment of the TB patients in the Sweeney3 signature (Figure 1F; Null_{AUC} = 0.63 [95% CI (0.45–0.82)] and TB Ag_{AUC} = 0.51 [95% CI (0.32–0.71)], (p = 0.4) or the RISK11 signature (Supplementary Figure S1F; Null_{AUC} = 0.57

[95% CI (0.38–0.77)] and TB Ag_{AUC} = 0.63 [95% CI (0.45–0.81)] (p = 0.7), confirming the specificity of these signatures.

In summary, immune stimulation revealed multiple differences between latent *M.tb* infection and active TB disease that likely reflect relative differences in ISG expression in blood

leukocytes, which may help to better understand perturbed immunity during TB pathogenesis and potentially improve new diagnostic strategies.

The IL-1 pathway is dysregulated in active TB disease

The TB Ag stimulation illustrated in [Figures 1D, E](#) captures differences in antigen-specific responses of CD4⁺ T cells, and subsequent downstream responses, between LTBI and TB patients. To explore the broader impact of TB disease in mounting efficient immune responses to complex stimuli, we investigated the response to BCG. To identify immune pathway differences, we performed correlation analysis between BCG-induced cytokines at the protein level (Fold-change > 1.3 in the BCG condition respect to the Null) in the LTBI and TB groups ([Figure 2A](#)). This revealed negative correlations in the control LTBI group, that were absent or markedly weaker in TB patients, suggesting altered regulation of cytokine production in TB disease. This included several key cytokines important for immune responses against TB such as IL-1 α , IL-1 β , IL-10, GM-CSF (CSF2) and TNF, which all showed a positive correlation with the IL-1 receptor antagonist (IL-1ra) in TB patients ([Figure 2A](#) right panel), in contrast to a negative correlation in LTBI ([Figure 2A](#) left panel).

Because IL-1 signalling is essential for *M.tb* control ([20](#)) and three key members of the IL-1 family (IL-1 α , IL-1 β and IL-1ra) showed significant differences, we focused on understanding the distinct secretion of IL-1 family cytokines between LTBI and TB. We started by investigating levels of IL-1ra and observed that TB patients presented higher concentrations of IL-1ra both at baseline and after BCG stimulation ([Figure 2B](#)). Here, we explore underlying mechanisms of differential IL-1ra secretion at baseline ([Figures 2, 3](#)) and after BCG stimulation ([Figure 4](#)). To better understand the drivers of IL-1ra secretion at baseline in TB, we performed correlation analysis of the protein data comprising 40 cytokines/chemokines in the Null tube and showed that the strongest association ($r=0.52$, $p=0.0001$) was with IL-8 ([Figure 2C](#)), a cytokine which also had significantly higher levels in TB patients ([Figure 2D](#)). Expression levels of both IL-8 receptors (CXCR1 and CXCR2) were also higher in TB patients ([Figure 2E](#)), however stimulation of blood from healthy controls with IL-8 did not induce IL-1ra ([Figure 2F](#)). We next explored gene expression signatures commonly associated with these two cytokines and found genes related to the peroxisome proliferator-activated receptor (PPAR) γ pathway ([Figure 2G](#)). We validated our findings using a published dataset of transcriptional analysis of human monocyte-derived macrophages (hMDMs) infected with different bacterial strains ([19](#)). This showed a weak, yet significant positive correlation ($r=0.34$, $q=0.03$) between IL1RN (the transcript for IL-1ra) and PPARG transcripts in hMDMs infected with mycobacteria, but not

with non-mycobacterial species ($r= -0.28$, $q=0.1$) ([Figure 2H](#)). These results suggest an immuno-metabolic link between the PPAR γ pathway and the receptor antagonist IL-1ra.

Pregnane steroids correlate with increased IL-1ra secretion in active TB at baseline, potentially through activation of the PPAR γ pathway

PPAR γ is a ligand-activated transcription factor that plays an essential role in metabolism and energy homeostasis, particularly in adipogenesis ([21, 22](#)). To explore potential metabolic pathways involved in IL-1ra secretion, we performed unsupervised mass spectrometry analysis on supernatants from unstimulated LTBI and TB patients' blood and examined which metabolites correlated with IL-1ra protein at baseline in the TB group. Interestingly, 5 of the top 6 ranked metabolites showing significant correlations ($r>0.6$, $q \leq 0.05$) with IL-1ra in TB patients belonged to pregnane steroid derivatives ([Figure 3A](#) and [Supplementary Table S5](#)). These correlations were observed in TB patients, and not in LTBI ([Figures 3A, B](#)). Interestingly, levels of these steroids did not differ between the LTBI and TB groups ([Supplementary Figure S2A](#)), in contrast to PPARG expression, which was higher in TB ([Supplementary Figure S2B](#)). Pregnane steroids have been shown to be potential ligands of PPAR γ ([23](#)), and PPAR γ is mainly expressed by CD14⁺ monocytes (Human Cell Atlas). To investigate whether activation of PPAR γ could drive IL-1ra secretion, we incubated CD14⁺ monocytes isolated from healthy donors, with combinations of the PPAR γ agonist rosiglitazone and the PPAR γ antagonist GW9662, in the presence of BCG. We validated our approach by measuring surface expression of CD36, a fatty acid translocase that is up-regulated by PPAR γ ([24–26](#)). CD14⁺ monocytes stimulated with rosiglitazone upregulated CD36, and this could be prevented with GW9662 ([Supplementary Figure S2C](#)). We observed that PPAR γ activation through rosiglitazone increased IL-1ra secretion by CD14⁺ monocytes, which could be inhibited by GW9662 ([Figure 3C](#)). To further confirm the role of PPAR γ in IL-1ra secretion, we silenced PPAR γ using small interfering RNA (siRNA). We confirmed PPAR γ knockdown in CD14⁺ monocytes by measuring levels of PPAR γ protein by flow cytometry ([Supplementary Figure S2D](#)). Both at baseline and after BCG stimulation, silencing of PPAR γ resulted in decreased IL-1ra secretion ([Figure 3D](#)), with this knockdown impacting both conditions equally ([Figure 3E](#)). This suggests that, in healthy volunteers, the PPAR γ pathway is not involved specifically in BCG-induced IL-1ra, although these data confirm PPAR γ as a potential regulator of baseline IL-1ra production in TB disease.

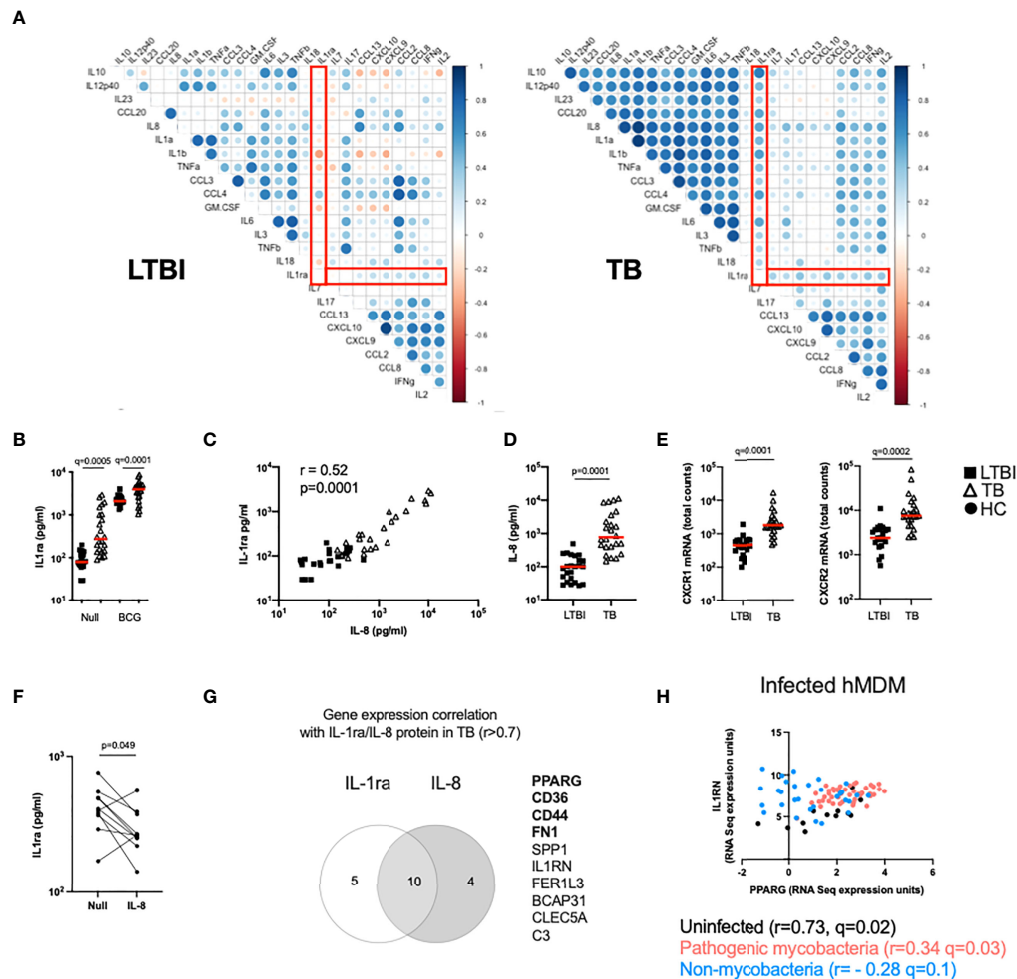


FIGURE 2

The IL-1 pathway is dysregulated in active TB disease. **(A)** Spearman correlation plot of the induced (Fold-change>1.3 in the BCG condition respect to the Null) proteins measured by Luminex in TruCulture supernatants after BCG stimulation for LTBI and TB. Red rectangles highlight IL-1ra correlations. **(B)** Levels of IL-1ra protein measured by Luminex in the Null and BCG conditions for LTBI and TB. **(C)** Spearman correlation between IL-8 and IL-1ra protein levels measured by Luminex in the Null condition, for LTBI and TB. **(D)** IL-8 concentration measured by Luminex in the Null condition, for LTBI and TB. **(E)** Gene expression levels of the IL-8 receptor subunits CXCR1 and CXCR2 measured by Nanostring at baseline. **(F)** IL-1ra protein concentration measured by ELISA in supernatants of whole blood from healthy individuals stimulated with IL-8 ($n=10$, 4 independent experiments). **(G)** Venn diagram of the genes correlated with IL-1ra and IL-8 in the Null condition in TB, measured by Nanostring and Luminex, respectively. Genes associated with the PPAR γ pathway are in bold. **(H)** Reanalysis of RNAseq data by Spearman correlation between PPAR γ and IL1RN gene expression levels of human monocyte-derived macrophages infected with mycobacterial (*M.tb* H37Rv, heat-inactivated *M.tb* H37Rv, *M.tb* GC1237 and BCG) and non-mycobacterial (*Yersinia pseudotuberculosis*, *Salmonella typhimurium* and *Staphylococcus epidermidis*) species for 18 and 48h (19). Comparisons between groups were performed using unpaired or paired (F) non-parametric t-tests and correction for multiple comparisons was applied. Red line: median values. Closed square: LTBI, Open triangle: TB, Closed circle: Healthy Control (HC). For panels (B, E), q values (false discovery rate-adjusted p values) are reported.

TNF signaling promotes IL-1ra secretion in BCG-stimulated blood

TB patients secreted higher protein levels of IL-1ra both at baseline and after BCG stimulation compared to LTBI (Figure 2B). The differences in IL-1ra secretion between TB and LTBI after BCG stimulation could not be explained by PPAR γ (Figure 3E). Therefore, we investigated the drivers of IL-1ra secretion in the context of BCG stimulation. Previous studies

have identified TNF, IL-1 and type I and II IFNs as drivers of IL-1ra secretion (27–32). To test this in our system we stimulated whole blood from healthy individuals with TNF, IL-1 β , IFN γ , IFN β , IFN α , and IL-8 and confirmed TNF and IFN β ($q=0.001$) as the strongest inducers of IL-1ra (Figure 4A). Furthermore, TNF and type I IFNs acted synergistically in inducing IL-1ra, as the combination of these cytokines (TNF + IFN α/β) resulted in a 4-fold higher induction as compared to stimulation with each cytokine alone (Figure 4B). We then investigated the effect of

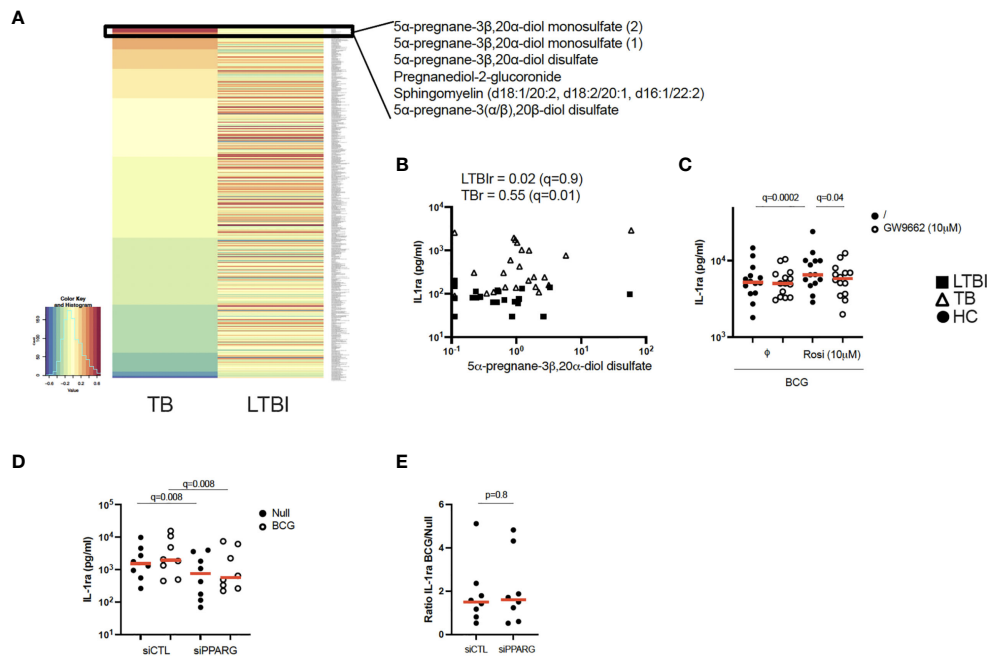


FIGURE 3

Pregnanediol-2-glucuronide activates the PPAR γ pathway resulting in increased IL-1ra secretion in active TB. **(A)** Heatmap of Pearson correlation coefficients between metabolites and IL-1ra protein in the Null condition, measured by mass spectrometry and Luminex, respectively, for TB (left) and LTBI (right). Metabolites are ordered in decreasing values of TB cases Pearson correlation coefficients. **(B)** Pearson correlation between IL-1ra levels measured by Luminex and 5 α -pregnane-3 β ,20 α -diol disulfate measured by mass spectrometry for LTBI and TB. **(C)** IL-1ra protein concentration measured by ELISA after stimulation of CD14 $^{+}$ monocytes from healthy individuals with BCG in the presence or absence of the PPAR γ agonist rosiglitazone (Rosi) and/or the PPAR γ antagonist GW9662 (n=14, 4 independent experiments). **(D)** IL-1ra protein concentration measured by ELISA after stimulation with BCG of PPARG silenced or control CD14 $^{+}$ monocytes from healthy individuals (n=8, 3 independent experiments). **(E)** Ratio of IL-1ra induced upon BCG stimulation versus the Null Control in PPARG silenced or control CD14 $^{+}$ monocytes (n=8, 3 independent experiments). Comparisons between groups were performed using paired non-parametric t-tests and correction for multiple comparisons was applied. Red line: median values. Closed square: LTBI, Open triangle: TB, Circle: Healthy Control (HC). For panels **(B–D)**, q values (false discovery rate-adjusted p values) are reported.

blocking IFN and TNF signalling through the use of blocking antibodies. Blocking of TNFR ($q=0.001$), but not IFNAR ($q=0.7$), resulted in significantly less IL-1ra production (Figure 4C). To obtain further insight into the potential contribution of TNF and type I IFN in IL-1ra production upon BCG stimulation, we examined a previously published kinetic study of BCG stimulated whole blood (33). This consisted of five healthy donors at 13 time points within 30h of BCG stimulation from which we measured IFN α and IFN β to analyse with existing TNF and IL-1ra data. A time-dependent linear regression on IL-1ra using IFN α , IFN β and TNF protein secretion as predictors revealed a strong association with TNF ($q=0.002$) but not type I IFNs (IFN α $q=0.6$, IFN β $q=0.6$) (Figure 4D). IFN β was not induced upon BCG stimulation, and IFN α was induced by BCG from the 10h time point (Figure 4D).

To apply these findings to TB patients, we measured TNF protein after BCG stimulation and observed that levels of TNF were surprisingly higher in LTBI compared to TB (Figure 4E). We next examined expression levels of the TNF receptor subunit (TNFRSF1B) and observed significantly higher levels ($q=0.0001$) in TB patients (Figure 4F), which may reflect increased signalling. To test this hypothesis, we calculated a gene score based on unique cytokine-induced gene signatures (see Materials and Methods and Supplementary Table S6) as previously described (15). The TNF gene score, which is a surrogate for quantifying signalling by this cytokine, was higher in the TB group compared to LTBI after BCG stimulation (Figure 4G), and also positively correlated ($R_s=0.32$, $p=0.03$) with IL-1ra protein concentrations (Figure 4H). These results suggest a role for TNF in BCG-induced IL-1ra, a response that is augmented in active TB disease.

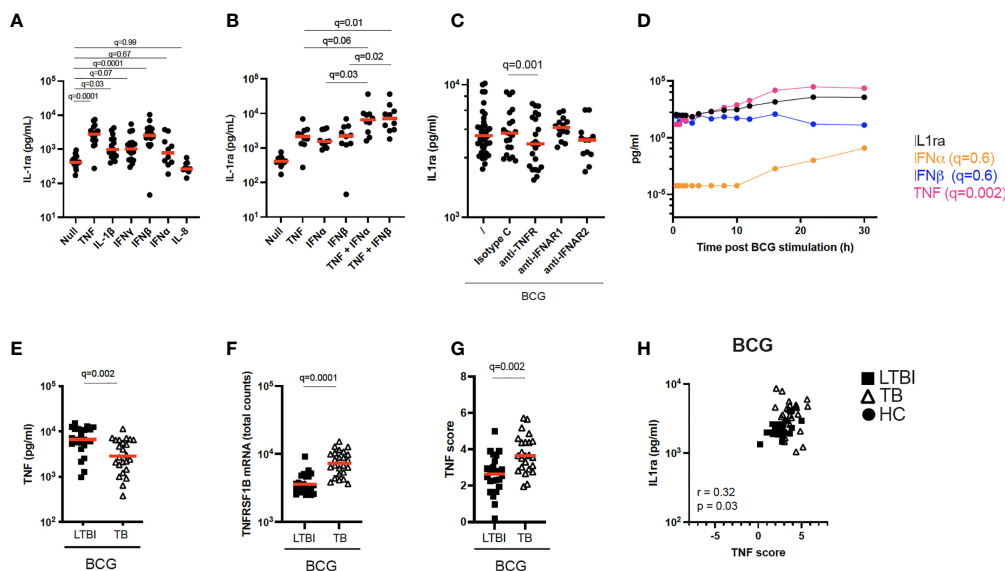


FIGURE 4

Increased TNF signaling promotes IL-1ra secretion. (A) Concentrations of IL-1ra measured by Luminex after stimulation of whole blood from healthy individuals with TNF (10 ng/ml), IL-1 β (25 ng/ml), IFN γ (1000 IU/ml), IFN α (1000 IU/ml), IFN β (1000 IU/ml), and IL-8 (25 ng/ml) (n=17, 4 independent experiments). (B) IL-1ra protein concentration measured by ELISA after whole blood stimulation with TNF, IFN α , IFN β , TNF + IFN α and TNF + IFN β (n=10, 3 independent experiments). (C) IL-1ra protein concentration measured by ELISA after whole blood stimulation with BCG in the presence of anti-TNFR or anti-IFNAR, or their respective isotype controls (Minimum n=12, 3 independent experiments). (D) Kinetics of IL-1ra, IFN α , IFN β and TNF secretion measured by Luminex (IL-1ra and TNF) and Simoa (IFN α and IFN β) upon BCG stimulation during the course of 30h. 1 representative donor of five healthy individuals is shown. (E) TNF protein concentration measured by Luminex in the BCG stimulated condition, for LTBI and TB. (F) TNFRSF1B mRNA expression levels measured by Nanostring in the BCG stimulated condition, for LTBI and TB. (G) TNF gene score in the BCG stimulated condition for the LTBI and TB groups. (H) Spearman correlation between IL-1ra levels and TNF gene score in the BCG stimulated condition. For calculation of TNF score see Materials and methods and [Supplementary Table S6](#). Paired (A–C) and unpaired (E–G) non-parametric t-test corrected for multiple comparisons. Red line: median values. Closed circle: Healthy Controls, Closed square: LTBI, Open triangle: TB. For panels A–G, q values (false discovery rate-adjusted p values) are reported.

TB patients present lower granzyme concentrations and lower levels of functional IL-1 α and IL-1 β after BCG stimulation

BCG stimulation revealed dysregulation of multiple arms of the IL-1 pathway in active TB disease ([Figure 2A](#)). As well as observing differentially induced IL-1ra between LTBI and TB ([Figure 2B](#)), we also saw significant differences in IL-1 α and IL-1 β secretion ([Figure 5A](#)). In contrast to IL-1ra, both IL-1 α and IL-1 β protein were secreted at significantly higher levels in LTBI upon BCG stimulation. However, these differences were not mirrored at the transcript level ([Figure 5B](#)). We therefore hypothesized that post-transcriptional/post-translational modifications might be impaired during active TB disease. IL-1 β requires post-translational cleavage to signal and engage functional outcomes, whereas IL-1 α can manifest basal levels of activity in its unprocessed form (34). As this protein processing can occur through either inflammasome-dependent or independent manners (34, 35) we explored whether both pathways were engaged in our whole blood stimulation system. We stimulated blood from healthy donors with BCG in

combination with either the selective NLRP3 inflammasome inhibitor MCC950, the Syk inhibitor R406 (e.g. it inhibits the NLRP3 inflammasome and C-type-lectin receptors [CLRs]), a serine-protease inhibitor (3,4-Dichloroisocoumarin, DCI) capable of blocking a range of enzymes involved in inflammasome-independent cleavage of IL-1 immature proteins, including granzymes and cathepsins. Treatment with R406 and DCI, but not MCC950, resulted in a partial but significant reduction of IL-1 β secretion after BCG stimulation ([Figure 5C](#)), suggesting a role for Syk-proteins outside the NLRP3 inflammasome, and serine-proteases in the secretion of IL-1 β in stimulated whole blood cultures.

We then examined differences in these pathways between LTBI and TB patients. The transcripts of components from different inflammasomes (i.e. NLRP3, NLRC4, AIM2) NLRP3, SYK, CARD9 and CASP1 were significantly more expressed after BCG stimulation in TB patients compared to LTBI ([Figure 5D](#)). Cathepsin G, a neutrophil serine-protease that cleaves pro-IL-1 β , was also expressed at higher levels in the TB group ([Figure 5E](#)), whereas no differences were observed in cathepsin C transcripts. In contrast, other genes that participate in inflammasome-independent IL-1 cleavage, such as granzymes

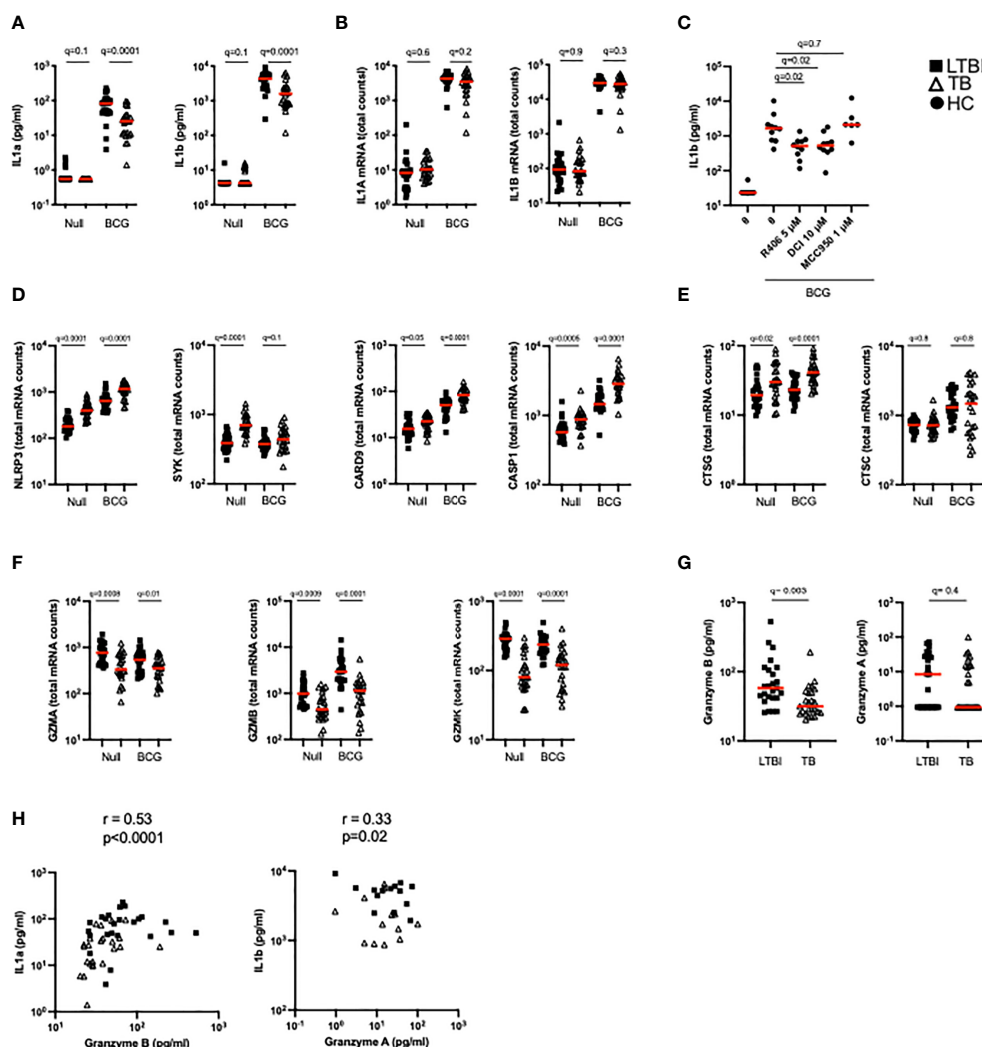


FIGURE 5

TB patients present lower granzyme concentrations which impact levels of functional IL-1 α and IL-1 β . (A) Levels of IL-1 α and IL-1 β protein measured by Luminex in the Null and BCG stimulated conditions. (B) Levels of IL1A and IL1B mRNA measured by Nanostring in the Null and BCG conditions. (C) BCG stimulation of healthy donor blood with the NLRP3 inhibitor MCC950 (1 μ M), the Syk inhibitor R406 (5 μ M) or the serine-protease inhibitor 3,4-Dichloroisocoumarin (10 μ M) ($n=7$, 2 independent experiments). Levels of mRNA expression for inflammasome components NLRP3, SYK, CARD9 and CASP1 (D), cathepsins (E) and granzymes (F) measured by Nanostring in the Null and BCG conditions for TB and LTBI. (G) Granzyme A and granzyme B protein concentrations in TruCulture BCG supernatants for TB and LTBI measured by Luminex. (H) Spearman correlation between protein concentrations of granzyme B and IL-1 α , and granzyme A and IL-1 β in BCG supernatants. Paired (C) and unpaired non-parametric t-test corrected for multiple comparisons. Red line: median values. Closed square: LTBI, Open triangle: TB, Closed circle: Healthy Controls. For panels (A–G), q values (false discovery rate-adjusted p values) are reported.

A, B and K, were expressed at higher levels in the LTBI group (Figure 5F) suggesting that this pathway was more relevant for BCG induced IL-1 β . Concentrations of granzyme B in the BCG supernatants were higher in the LTBI group compared to TB, however, no significant differences were observed with granzyme A (Figure 5G). It was notable that most granzyme A levels were below the limit of detection of the assay. Levels of granzyme B

strongly correlated with IL-1 α ($R=0.53$, $p=0.0001$) and there was a moderate but significant ($R=0.33$, $p=0.02$) correlation between IL-1 β protein and Granzyme A (Figure 5H). These data support our hypothesis of aberrant IL-1 induction in TB disease, with lower levels of granzyme protein associating with reduced cleavage of IL-1 precursors, and thus less active forms of IL-1 cytokines.

Table S8). Our data shows that IL-1 β signalling is strongly perturbed in active TB disease, and this response is restored after successful treatment.

Discussion

A better understanding of how TB disease impacts immune responses is required for improved design of novel host-directed therapies. Here, we investigated differences in TB Ag, BCG and IL-1 β induced immune responses between LTBI and TB patients using a standardised immunomonitoring system. Integration of transcriptomic, proteomic and metabolomic data sets at baseline and after immune stimulation revealed altered immune and metabolic pathways in TB disease. Previous studies have identified immune and metabolic differences in unstimulated whole blood of TB patients (36–38). However, this approach is limited when studying impaired responses to immune challenges. Using TruCulture we identified and dissected how members of the IL-1 family, which are key cytokines for *M.tb* control, are perturbed in TB disease. The potential clinical relevance of such an approach was illustrated by the observation that immune stimulation improved the diagnostic score of a previously described gene expression signature for TB diagnosis (17).

The antagonist IL-1ra molecule was elevated in TB at baseline conditions. Despite this cytokine having been proposed as a potential biomarker to distinguish LTBI from active TB (10), the biological triggers of IL-1ra in the context of TB remain largely unknown. We showed that increased basal levels of IL-1ra in TB patients are associated with the PPAR γ pathway. PPAR γ is constitutively and highly expressed in healthy alveolar macrophages (39, 40), and has been shown to regulate host immune and metabolic responses to mycobacterial infection (41). *M.tb*-driven activation of PPAR γ promotes IL-8 secretion (42), and activation of PPAR γ in THP-1 cells results in IL-1ra secretion (43), in agreement with our observations. Furthermore, Pott and colleagues identified IL1RN as a putative PPAR γ target gene in a THP-1 model of human macrophages (44). We propose a model in which pregnane steroids in TB disease activate the PPAR γ pathway, which may act at different levels (eg. CD36, IL-1ra) to promote *M.tb* replication. *M.tb* can promote CD36 expression through PPAR γ activation (45), and CD36 contributes to *M.tb* survival (46, 47). Finally, the PPAR γ axis can trigger IL-1ra secretion (43), which inhibits IL-1 signalling, essential for pathogen clearance (20). Inhibition of PPAR γ has been associated with decreased mycobacterial burden in mouse and human macrophages (41, 42, 45) and deletion of PPAR γ in lung macrophages has been shown to be immunoprotective in the context of *M.tb* infection in mice (48). PPAR γ is therefore a good host-directed therapeutic target candidate, as it impacts lipid body biogenesis, cytokine production and *M.tb* replication (49).

PPAR γ agonists are already being used in the treatment of conditions such as diabetes, where they act as insulin sensitizers (50). Diabetes prevalence is escalating globally and the increasing overlap with TB is a major source of concern, with type 2 diabetic patients having a 3-fold increased risk of developing TB (51). Activating PPAR γ agents would be predicted to enhance susceptibility to TB disease. Therefore, careful assessment of how metabolic modulators impact comorbidities is required.

Stimulation with BCG revealed perturbed IL-1 family cytokine responses in TB patients, which is crucial for host control of *M.tb* infection (7, 52, 53). Specifically, TB patients simultaneously had lower agonist (IL-1 α and IL-1 β) and higher antagonist (IL-1ra) responses. Detailed kinetic studies (33), combined with single cytokine stimulations (15), blocking experiments, and time series analysis permitted the identification of TNF as key driver of IL-1ra in TB disease. These results add to the existing complexities of cytokine responses to *M.tb*, in which the overall context will determine infection outcome, rather than the presence/absence of particular cytokines. For instance, the timing of IL-1 (54, 55) or type I IFN signalling (56) is a decisive factor to exert beneficial roles in the context of TB disease. Our study shows how TNF, a critical cytokine for control of *M.tb*, also induced IL-1ra expression, which can prevent effective IL-1 responses, that are in turn essential for protective immunity.

The observed IL-1 α and IL-1 β protein differences were not mirrored at the transcriptional level, suggesting defects in either post-transcriptional or post-translational regulation. Notably, both IL-1 α and IL-1 β require enzymatic post-translational cleavage, which can occur through inflammasome-dependent or -independent mechanisms (57). *M.tb* has previously been shown to inhibit inflammasome activation and IL-1 β processing (58), and a recent study demonstrated that CARD9, an inflammasome protein associated with fungal induction of proinflammatory cytokines, negatively regulated IL-1 β production during bacterial infection (59). It has also been shown that IL-1 β production in *M.tb* infection can take place independently of caspase-1 and ASC-containing inflammasomes in mice (53). In our study we observed both higher inflammasome activity and lower granzyme expression in TB patients. Thus, lower granzyme activity in TB patients may result in lower post-translational cleavage of IL-1 α/β . This is supported by previous studies in which PBMC stimulation with *M.tb*-related antigens resulted in lower levels of granzyme B in TB patients (60). In addition, a recent multi-cohort study identified granzyme B, produced by polyfunctional NK cells, as a characterising feature of LTBI compared to uninfected controls (61).

We and others have reported distinct secretion of IL-1 agonists and antagonists upon *M.tb* infection (10, 20, 62), however, whether IL-1 signalling itself is impaired in TB disease remains poorly explored. Here, we report higher

expression of most IL-1 β -induced genes in TB compared to LTBI before treatment (Figure 6A, left panel). This observation shows that there is no intrinsic defect in IL-1 β signalling capabilities in TB patients. However the timing of IL-1 responses has been shown to be critical for *M.tb* control (54, 55) and elevated IL-1 signalling has been associated with lung immunopathology (63, 64). The consequences of IL-1 β hyper responsiveness in TB patients therefore warrants further investigation. Importantly, the elevated IL-1 β signalling was no longer present after successful antibiotic treatment (Figure 6A, right panel), suggesting that immune responses were reset to healthy levels. A limitation of the current study is that experiments were performed on peripheral blood, whereas the cytokine networks that regulate *M.tb* infection *in vivo* also act on tissue resident cells, which might behave differently. Also, cellular differences between the groups studied, such as higher monocyte-to-lymphocyte and neutrophil-to-lymphocyte ratios in active TB compared to LTBI (65), could potentially contribute to some of the observed differences.

The current study presents certain limitations. We showed that whole blood stimulation with *M. tb* antigens increases the current diagnostic value of well-established gene expression signatures (Figure 1E and Supplementary Figure 1E). Although this finding has potential clinical impact, an additional requirement for sample stimulation is a significant practical limitation for TB diagnosis in real world clinical settings.

Following up on the novel correlation observed between pregnane steroids and circulating IL-1ra protein levels in TB patients, it would have been ideal to provide direct evidence that pregnane steroids activate the PPAR γ pathway resulting in increased IL-1ra secretion in active TB infection. Unfortunately, these experiments are not currently possible as we do not have access to the pregnane steroids identified in Figure 3A. To overcome this limitation, we showed that PPAR γ agonists increased IL-1ra secretion (Figure 3C), and that silencing of PPAR γ resulted in decreased IL-1ra secretion (Figure 3D), both results in support of our hypothesis. Another drawback to acknowledge is the relatively limited functional data from patient-derived samples. Although we did report altered cytokine secretion after patient blood stimulation, we did not have further access to TB patient blood to provide comprehensive mechanistic explanations for the observed phenotypes, as we did for healthy individuals (e.g. Figures 3C, D). Nonetheless, we strongly believe that being able to show mechanistic links in CD14 $^{+}$ monocytes from healthy individuals (e.g. between PPAR γ -IL-1ra) constitutes a novel and very interesting finding, with relevance for TB disease.

In summary, our study of immune-metabolic responses revealed perturbed responses in TB disease at transcriptomic, proteomic and metabolomic levels. Integration of these datasets has improved our knowledge on how TB disease impacts immune-metabolic pathways resulting in perturbed IL-1

responses, which are essential for *M.tb* control. This better understanding of how *M.tb* alters immune responses may facilitate the improved design of preventive and therapeutic tools, including host-directed strategies.

Materials and methods

Participant groups

Adult patients with sputum Xpert MTB/RIF-positive TB disease who tested HIV-negative were identified and recruited at clinics in Worcester, South Africa (62). Healthy QuantiFERON-TB Gold (QFT) positive (*M.tb*-infected) adults were recruited from communities living in or around Worcester and those who matched TB cases by age and gender were enrolled as LTBI controls (Table 1). Blood was collected prior to treatment initiation in active TB cases and again 12-18 months later, after successful completion of treatment defined by clinical cure (V2, n=18). For the QFT+ controls, blood was also collected at a second time-point, 12-18 months after the initial visit (V2, n=19). The TB clinical study protocols and informed consent forms were approved by the Human Research Ethics Committee of the University of Cape Town (ref: 234/2015). Healthy donor blood was obtained from the CoSImmGEN cohort of the Investigation Clinique et Accès aux Ressources Biologiques (ICAREB) platform, (Centre de Recherche Translationnelle, Institut Pasteur, Paris, France) or from the *Etablissement français du sang* (EFS, France). Blood was collected in sodium-heparin tubes. Written informed consent was obtained from all study participants.

TABLE 1 Tuberculosis cohort characteristics.

	TB Patients	LTBI controls	p value
Age (median years, IQR)	33 (25-40)	33 (24-41)	0.89
Sex (% female)	24	24	>0.99
Ethnicity (% Cape Mixed ancestry)	72	76	>0.99
Household TB contacts (%yes)	56	40	0.26
BMI (media, IQR)	20 (19-21)	26 (24-28)	<0.0001
Smoking (n)			0.07
Smoker	14	0	
Ex-smoker	7	2	
Non-smoker	4	10	
Visit 1 (n° donors)	24	24	NA
Visit 2 (n° donors)	18 (after treatment)	19	NA

TB, tuberculosis; LTBI, Latent tuberculosis infection; IQR, Interquartile range; NA, Non applicable.

TruCulture whole blood stimulation

TruCulture tubes were prepared in batch as previously described (14, 15) with the following stimuli: QFT antigens (ESAT-6, CFP-10, TB7.7), *Bacillus Calmette–Guérin* (BCG; Sanofi Pasteur, 10⁵ units/ml), and IL-1 β (Peprotec, 25 ng/ml). They were resuspended in 2 ml of buffered media and maintained at -20°C until use. Blood was collected in sodium-heparin tubes (50 IU/ml final concentration). Within 30 min of collection, 1 ml of whole blood was distributed into pre-warmed TruCulture tubes, inserted into a dry block incubator, and maintained at 37°C (+/- 1°C), room air for 22 hr (+/- 15 min). After incubation, a valve was inserted to separate cells from the supernatant and to stop the stimulation reaction. Upon removal of the liquid supernatant, cell pellets were resuspended in 2 ml Trizol LS (Sigma), vortexed for 2 min, and rested for 10 min at room temperature before -80°C storage. Cytokine kinetic secretion data sets were previously described (33). All stimulations were performed for 22h unless otherwise specified.

Isolation and culture of blood leukocytes from healthy donors

For monocyte experiments, blood was collected in buffy coats from healthy donors sampled at the EFS, France. First, PBMCs were isolated by density centrifugation from peripheral blood leukocyte separation medium (Ficoll-PaqueTM plus; GE Healthcare). Human monocytes were purified by negative selection with the classical monocyte isolation kit (Miltenyi). Monocytes were cultured at 1x10⁶ cells/mL in RPMI 1640 (Invitrogen, Gaithersburg, MD) (R10) containing 10% heat-inactivated fetal bovine serum, penicillin (100 U/ml), streptomycin (100 μ g/ml; 1% pen-strep), and 1 mM glutamine (HyClone, Logan, UT).

Protein analysis

Supernatants from TruCulture tubes were thawed on ice and tested by Luminex xMAP technology for a total of 32 proteins including cytokines, chemokines and growth factors as previously described (14). Samples were measured on the Myriad RBM Inc platform (Austin, Texas, US) according to CLIA guidelines (set forth by the USA Clinical and Laboratory Standards Institute). The least detectable dose (LDD) for each assay was derived by averaging the values obtained from 200 runs with the matrix diluent and adding 3 standard deviations to the mean. The lower limit of quantification (LLOQ) was determined based on the standard curve for each assay and is the lowest concentration of an analyte in a sample that can be reliably detected and at which the total error meets CLIA

requirements for laboratory accuracy. IL-1 β , IL-1ra, IL-1 α , IL-6, IP-10 and Granzyme A/B were also measured using Human ELISA Kit (ThermoFischer Scientific) or Human Custom Procarta-plexes (ThermoFischer Scientific), following manufacturer's instructions.

To detect low concentrations of cytokines homebrew Simoa digital ELISA were used for IFN α (66) and IFN β (67), as previously described.

Gene expression analysis

Cell pellets in Trizol LS were thawed on ice for 60 min prior to processing. Tubes were vortexed twice for 5 min at 2000 rpm and centrifuged (3000 x g for 5 min at 4°C) to pellet the cellular debris generated during lysis. RNA was isolated from whole blood samples using the NucleoSpin 96 RNA tissue kit protocol (Macherey-Nagel) with some modifications as previously described (15).

RNA integrity was assessed (Agilent RNA kits for the 2100 Bioanalyzer System). The NanoString nCounter system was used for the digital counting of transcripts. RNA was quantified using the Qubit RNA HS Assay Kit (Thermo Fischer Scientific) and 100ng of total RNA hybridized with the Human Immunology v2 (plus 30 additional genes (Supplementary Table S1) relevant for TB that were included) Gene Expression CodeSet according to the manufacturer's instructions. Samples were processed in 7 batches (4 for Visit 1, 3 for Visit 2), within which the samples were randomized, and the same lot of reagents was used for all samples. All samples were normalized together following background subtraction of the negative control probes, using positive control probes and housekeeping genes (SDHA, HPRT1, POLR2A, RPL19, G6PD, TBP) selected by the GNorm method as previously described (68). This was done using the nSolverTM analysis software (NanoString technologies). Quality control for our data involved checking the following metrics: fields of view counted (flag if < 0.75), binding density (flag if not in the 0.05-2.75 range), linearity of positive controls (flag if R² < 0.9) and limit of detection for positive controls (flag if 0.5 fM positive control < 2 SDs above the mean of the negative controls).

Metabolomic analysis

Supernatants from TruCulture Null tubes were thawed and tested by Ultrahigh Performance Liquid Chromatography-Tandem Mass Spectroscopy (UPLC-MS/MS) for a total of 696 metabolites. Samples were measured on the Metabolon Inc platform (Morrisville, North Carolina, US). For metabolite quantification, peaks were quantified using area-under-the-curve. A data normalization step was performed to correct

variation resulting from instrument inter-day tuning differences, and values were rescaled to set the median equal to 1. Missing values were imputed with the minimum.

Chemical inhibitors, agonists and antagonists

The NLRP3-specific inhibitor MCC950, the inhibitor of Syk phosphorylation R406 (*In vivogen*) and the serine-protease inhibitor 3,4-Dichloroisocoumarin (Sigma Aldrich) were used at 1 μ M, 5 μ M and 10 μ M, respectively. The PPAR γ agonist Rosiglitazone (Sigma-Aldrich) and the antagonist GW9662 (Sigma-Aldrich) were used at 10 μ M. All drugs were added 1h before BCG stimulation.

Cytokine stimulation and blocking experiments

Whole blood from healthy donors was pre-incubated with antibodies or a relevant isotype control at 10 μ g/mL for 1h (unless otherwise stated), using the following: anti-human CD120a (Clone MABTNFR1-B1, BD Bioscience) antibody, anti-human Interferon alpha/beta receptor 1 antibody (Anifrolumab), anti-human Interferon alpha/beta receptor 2 antibody (PBL, clone MMHAR-2). Whole blood was then diluted 1/3 in TruCulture media and stimulated with BCG or with selected human recombinant cytokines for 22h at 37°C, as follows: IFN α (IntronA; 1000 IU/mL), IFN β (Betaferon; 1000 IU/mL), IFN γ (Peprotec; 25 ng/mL), IL-1 β (Peprotech; 25 ng/mL), TNF (Miltenyi; 10 ng/mL), IL-8 (Biolegend; 25 ng/mL).

siRNA experiments

Monocytes were seeded at 2×10^5 cells/200 μ l in 96-well plates and incubated at 37°C. Cyclophilin B (control) and PPAR γ siRNA (SMARTPool, Dharmarcon) were diluted in DOTAP (1,2-dioleoyl-3-trimethylammonium-propane; Roche Applied Sciences). The mix was gently mixed and incubated at room temperature for 15 min. After incubation, the mix was added to cells in culture at a final concentration of 160 nM. Cells were then incubated at 37°C for 24 hours before adding BCG stimulation for 16 hours.

Flow cytometry – CD36 & PPAR γ

Cells were washed in PBS and resuspended in PBS containing 2% fetal calf serum and 2 mM EDTA and stained with the extracellular mix using anti-human CD14-BV421

antibody (clone M5E2, BD Bioscience) and anti-human CD36-BUV605 antibody (clone CD38, BD Bioscience) at 1:200. For PPAR γ intracellular staining, a Fixation/Permeabilization Solution Kit (BD Cytfix/Cytoperm) was used according to the manufacturer's protocol. Briefly, the cells were fixed for 10 min at 4°C with 100 μ L of the Fixation/Permeabilization solution and then washed and stained in 100 μ L of the BD Perm/Wash Buffer containing anti-human polyclonal PPAR γ antibody (PA3-821A, Invitrogen) at 1:25 for 1 hour at 4°C. Goat anti-rabbit IgG-Alexa Fluor 700 was used as a secondary antibody at 1:1000 (ThermoFisher Scientific). Data acquisition was performed on a FACS LSR flow cytometer using FACSDiva software (BD Biosciences, San Jose, CA). FlowJo software (Treestar, Ashland, OR) was used to analyze data.

Statistical analysis, data visualization, and software

ANOVA (Kruskal-Wallis) testing was performed for multi-group comparisons and paired t-tests for intra-patient analysis with Qlucore Omics Explorer, v.3.2 (Qlucore) or GraphPAD Prism. To correct for multiple testing we report false discovery rate (FDR)-adjusted ANOVA p values; q values. Dot plot graphs were compiled with GraphPad Prism v.6.0, heatmaps and Principal Component Analysis (PCA) plots with Qlucore. ROC curves were calculated with R (v.3.4.4) and results drawn with graphical package ggplot2 (v.3.1.0). UpSet plots were drawn with UpSetR (v1.3.3), and correlations plots corrplot (v0.84).

Time series analysis on the protein secretion measurements, from 5 different donors, was conducted using a linear mixed-model approach. The time dependency was modelled by incorporating the parameter time as a continuous linear predictor, alongside the other protein predictors, and the donors were modelled as a random effect. The model was implemented using the R package 'lme' (v1.1-20).

For calculation of cytokine-specific genes score, the genes uniquely induced by each cytokine were identified from our previous study in healthy donors (15). The first Principal component of the expression matrix was computed using the PCA() function of the FactoMineR package (version 1.42) with the options "scale" set to TRUE, and the option "ncp" set to 1. Position of each sample on the first component was then extracted and used for further analysis (R v.3.6.1).

Pearson correlations were performed in R (v3.6.0) between IL-1Ra protein concentrations quantified by Luminex and the metabolites quantified through mass spectrometry for either TB or LTBI cases. To down-size the number of metabolites analyzed, only metabolites that belong to metabolic groups composed of at least 7 metabolites and that are not labelled as 'Drug' or 'Chemical' were considered. The metabolite and protein correlation heatmap was plotted with the ggplot2 R package (v.3.3.1).

Data availability statement

The data presented in the study are deposited in the EBI repository, accession numbers E-MTAB-12379 (transcriptomics), E-MTAB-12380 (proteomics) and E-MTAB-12381 (metabolomics).

Ethics statement

The studies involving human participants were reviewed and approved by Human Research Ethics Committee of the University of Cape Town (ref: 234/2015). The patients/participants provided their written informed consent to participate in this study.

Author contributions

AL designed and performed experiments, analysed and interpreted data and wrote the manuscript. NS designed and performed experiments, and analysed and interpreted data. VR analysed data. MM and EN performed experiments on the TB patient cohort. MM, CP, SM, BC, SKM, VS-A, VB, PB, HM and NB performed specific experiments and/or analysis. EF and HA were the clinical and laboratory study coordinators in South Africa, respectively. MLA, TJS and DD conceived the whole study, obtained funding and provided overall guidance. DD designed and supervised the whole study, designed experiments, analysed and interpreted data and wrote the manuscript. All authors contributed to manuscript revision, read and approved the submitted version.

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Conflict of interest

MLA is a current employee of HIBIO. VR was employed by DATACTIX.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fimmu.2022.897193/full#supplementary-material>

SUPPLEMENTARY FIGURE 1

(A) Scree plot showing the variance explained by each PCA component on the gene expression (Nanostring) dataset. (B) Examples of significantly different ($q < 0.001$) stimuli-specific induced transcripts between TB and LTBI. (C) Expression of the 3 genes from Sweeney3 (69) in the Null and TB Ag conditions on visit 2 post-treatment. (D) RISK11 score (18) in the Null and TB Ag conditions, pre and post-treatment, for the LTBI and TB groups, calculated using the Singscore method. Area under the receiver operating characteristic curve (AUC) for discrimination of LTBI/TB groups using the RISK11 score for the Null and TB Ag conditions on visit 1 pre-treatment (Pre-Tx) (E) and visit 2 after successful antibiotic treatment (Post-Tx) (F). Comparisons of LTBI/TB groups within the same stimulation were performed using unpaired non-parametric t-tests; comparisons between Null and stimulated conditions within the LTBI/TB groups were performed using a paired non-parametric t-test. Correction for multiple comparisons was then applied. Red line: median values. Closed square: LTBI, Open triangle: TB.

SUPPLEMENTARY FIGURE 2

(A) Relative levels of pregnane steroids identified in for both LTBI and TB, measured by mass spectrometry in the Null condition. (B) Gene expression levels of PPAR γ in the Null condition measured by Nanostring both in LTBI and TB. (C) Protein levels of CD36 measured by flow cytometry on the surface of CD14 $^{+}$ monocytes from healthy individuals in the presence or absence of the PPAR γ agonist rosiglitazone (Rosi) and/or the PPAR γ antagonist GW9662 ($n=13$, 5 independent experiments). (D) Intracellular protein levels of PPAR γ measured by flow cytometry in CD14 $^{+}$ monocytes from healthy individuals after treatment with PPAR γ small interfering RNA (siRNA) or control ($n=3$, 2 independent experiments). Comparisons between groups were performed using unpaired (A, B) or paired (C) non-parametric t-tests and correction for multiple comparisons was applied. Red line: median values. Closed square: LTBI, Open triangle: TB, Circle: Healthy Control (HC).

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