RIF1 acts as a gatekeeper of B cell identity during late differentiation

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Abstract

RIF1 is a multifunctional protein that promotes immunoglobulin (Ig) isotype diversification. Whether RIF1 plays additional roles in adaptive immunity is unknown. In this study, we showed that *Rif1* expression is upregulated following mature B cell activation, while its deficiency skewed the transcriptional profile of activated B cells towards plasmablasts (PBs) and plasma cells (PCs). Additionally, RIF1 ablation resulted in increased PB formation *ex vivo* and enhanced terminal differentiation into PCs upon immunization. Therefore, RIF1 serves as a cell identity gatekeeper during late B cell differentiation, providing an additional layer of control in the establishment of humoral immunity.

Keywords: mature B cells, differentiation, plasma cells, RIF1, transcription, BLIMP1

Running Title: RIF1 restrains terminal B cell differentiation

Introduction

Mature B cells are the crucial cell type that delineates the two main B cell lineage development phases. During early B cell development in the bone marrow, common lymphoid progenitors develop into immature B cells *via* a step-wise process linked to the rearrangement of their antibody receptor/immunoglobulin (Ig) genes by V(D)J recombination (Lin et al. 2018; Nemazee 2017). Immature B cells expressing a functional and non-autoreactive B cell receptor (BCR) migrate to the periphery, where they complete their maturation into quiescent resting cells (Lin et al. 2018; Nemazee 2017). The encounter of these naïve mature B cells with their cognate antigen in secondary lymphoid organs triggers late B cell differentiation into effector cells, often accompanied by further BCR/Ig diversification *via* somatic hypermutation (SHM) and class switch recombination (CSR) (Chandra et al. 2015). SHM and CSR provide the molecular bases for generating high-affinity and isotype-switched BCRs/Igs, respectively (Methot and Di Noia 2017). At the cellular level, the combined effect of BCR engagement and helper T cell-derived signals induces the formation of specialized microstructures known as germinal centers (GCs), where activated B cells undergo a major proliferative burst, selection of high-affinity BCR variants, and differentiation into either antibody-secreting cells (ASCs, plasmablasts (PBs) and plasma cells (PCs)) or memory B cells (Victora and Nussenzweig 2022). B cell activation can also lead to PB generation at extrafollicular sites, which are also characterized by B cell proliferation and represent the main source of ASCs in T-cell independent responses (Elsner and Shlomchik 2020). The generation of PBs and long-lived PCs capable of secreting high-affinity Igs of different classes provides the foundation for the establishment of protective humoral responses.

RIF1 (Rap1-Interacting Factor 1 Homolog / Replication Timing Regulatory Factor 1) is a multifunctional protein initially identified in budding yeast as a regulator of telomere length homeostasis (Hardy et al. 1992). In mammalian cells, RIF1 contributes to preserving genome stability during both DNA replication and repair. Under conditions of DNA replication stress, RIF1 protects nascent DNA at stalled forks from degradation, facilitating their timely restart (Ray Chaudhuri et al. 2016; Garzón et al. 2019; Mukherjee et al. 2019; Balasubramanian et al. 2022). During the repair of DNA double-strand breaks (DSBs), RIF1 participates in the 53BP1-Shieldin cascade that protects the broken DNA ends against nucleolytic resection, thus influencing the choice of which DSB repair pathway to engage (Chapman et al. 2013; Di Virgilio et al. 2013; Escribano-Díaz et al. 2013; Feng et al. 2013; Zimmermann et al. 2013). In addition to these genome-protective functions, RIF1 plays a central role in the control of DNA replication timing programs in both yeast and higher eukaryotes (Yamazaki et al. 2012; Foti et al. 2016; Gnan et al. 2021; Malzl et al. 2023). Several studies have also implicated RIF1 in early mouse development (Dan et al. 2014; Liu et al. 2023; Zhang et al. 2022; Li et al. 2015, 2022). This role appears independent from RIF1's various activities in DNA metabolism, and is mediated by its ability to modulate the transcriptional networks responsible for embryonic stem cell state stability and differentiation (Dan et al. 2014; Liu et al. 2023; Zhang et al. 2022; Li et al. 2015, 2022).

Isotype diversification by CSR occurs *via* a deletional recombination reaction at the Ig heavy chain (*Igh*) locus, which replaces the constant (C) region of the IgM/IgD basal isotype with one of the downstream C regions encoding for the different classes (IgG, IgE or IgA) (Methot and Di Noia 2017). The process necessitates the

formation of programmed *Igh* DSBs, which are physiologically protected from extensive resection to enable productive repair events and CSR (Saha et al. 2021). Due to its ability to inhibit DSB end processing, RIF1 is required for repair of *Igh* breaks, and hence for efficient Ig isotype diversification (Chapman et al. 2013; Di Virgilio et al. 2013; Escribano-Díaz et al. 2013). In this study, we report a novel role for RIF1 in the regulation of humoral immunity. We discovered that RIF1 expression is upregulated in mature B cells following activation, where it binds promoters of genes involved in B cell function and differentiation. RIF1 deficiency skews the transcriptional profile of activated B cells towards PBs and PCs, and is associated with an accelerated differentiation into ASCs both *ex* and *in vivo*. RIF1 directly binds several BLIMP1 target genes and counteracts their premature repression. Thus, by shaping mature B cell identity after activation, RIF1 contributes an additional regulatory layer to the B cell differentiation program that is essential to establish secreted antibody diversity.

Results and Discussion

Rif1 expression is regulated during B cell differentiation

To assess whether RIF1 contributes functions beyond the regulation of DNA end processing and repair in B cells, we first monitored *Rif1* expression levels across B cell lineage developmental stages using the Immunological Genome Project (ImmGen) transcriptomics data (The Immunological Genome Project et al. 2020). *Rif1* expression varied considerably in the different B cell subtypes, with GC cells exhibiting the highest levels (Fig. 1A). In contrast, the expression of RIF1's interactor partner in DNA repair, 53BP1, did not show any major changes during B cell development and differentiation (Fig. 1A). In addition, *ex vivo* activation of isolated naïve B cells (Fig. 1B and S1) resulted in upregulation of *Rif1*, but not *Tp53bp1*, transcript levels, regardless of the stimulation condition (LPS and IL-4 (LI); LPS, BAFF and TGFβ (LBT); or LPS (L)) and resulting isotype switching (IgG1, IgG2b, or IgG3, respectively) (Fig. 1, B and C). We concluded that, in contrast to *Tp53bp1*, *Rif1* expression is induced following activation of mature B cells both *in* and *ex vivo*.

RIF1 deficiency skews the transcriptional profile of activated B cells towards ASCs

We next assessed the consequences of RIF1 deficiency on the mature B cell transcriptome. To do so, we employed splenocyte cultures from $Rif1^{F/F}Cd19^{Cre/+}$ mice (Fig. 2A), which conditionally ablate *Rif1* expression at the immature B cell stage (Di Virgilio et al. 2013). Comparative assessment of the transcriptional profiles at different time points after activation identified only a limited number of considerably deregulated genes in the absence of RIF1 (N° genes with log2 FC < -1 and > 1 = 0,

105, and 47 at 48, 72, and 96 h, respectively) (Fig. 2B, S2, A and B, and Table S1). Furthermore, the expression of the mature B cell identity transcriptional regulators (*Pax5*, *Ebf1*, *Foxo1,* and *Bach2*) was not affected (Fig. S2C). These findings indicate that RIF1 is largely dispensable for the induction of the stimulation-dependent mature B cell program.

Activation of isolated splenocytes with specific stimuli recapitulates several features of terminal B cell differentiation (Shi et al. 2015; Minnich et al. 2016). Therefore, we next assessed the status of the key factors driving the ASC program (*Prdm1*, *Irf4*, and *Xbp1*). We found a near 2-fold increase in *Prdm1* transcript levels at 96 h after activation (Fig. 2B and S2C). Since the *Prdm1*-encoded transcription factor BLIMP1 is required for the differentiation of pre-PBs into PBs and PCs (Kallies et al. 2007; Minnich et al. 2016), we cross-referenced the list of differentially expressed genes (DEG, adjusted p-value < 0.05) from $Rif1^{F/F}Cd19^{Cre/+}$ activated B cells (Table S1) with the PB and PC signatures (Minnich et al. 2016) (see Supplemental Materials and Methods). We observed a significant overlap between DEGs and the corresponding up-/down-regulated gene set in the ASC signatures, with the tendency being more pronounced for the down-regulated datasets (Fig. 2C, S2D, and Table S2). We concluded that RIF1 deficiency in activated B cells results in a deregulated expression profile enriched in genes normally expressed in terminally differentiated B cells.

RIF1 limits the *ex vivo* differentiation of activated B cells into PBs and PC-like cells

Stimulation of naïve B cells with LPS and IL-4 induces their *ex vivo* differentiation into PBs at later time points after activation (96 h, (Scharer et al. 2018)). Therefore, we asked whether the skewed transcriptional profile exhibited by RIF1-deficient B cells reflects an altered potential for terminal differentiation. To this end, we compared the formation of PBs ($CD138^+$) in LI-stimulated B cells from $Cd19^{Cre}$ and $Rif1^{F/F}Cd19^{Cre}$ mice at 96 h post-activation. We found an over two-fold increase in the percentage of $CD138^+$ cells in RIF1-deficient samples compared to controls (Fig. 3A), thus indicating that the absence of RIF1 facilitates the *ex vivo* generation of PBs.

Currently, no *in vitro* setting can fully recapitulate the complexity of PC differentiation and function. However, the induced GC B (iGB) culture system ideated by Nojima *et al.* mimics the T cell-dependent generation of GC B cells and enables the *in vitro* manipulation of their fates into either memory- or long-lived PC-like cells (Nojima et al. 2011) (Fig. 3B). We took advantage of this system to assess the contribution of RIF1 to the terminal differentiation of activated B cells *ex vivo*. At the GC-like phenotype stage (four days stimulation with IL-4 on CD40L- and BAFF-expressing feeder cells), RIF1 deficiency resulted in the expected severe defect in CSR (Fig. 3, B and C) (Chapman et al. 2013; Di Virgilio et al. 2013; Escribano-Díaz et al. 2013). However, and in agreement with their increased potential to differentiate into PBs (Fig. 3A), $Rif1^{F/F}Cd19^{Cre}$ B cells showed a near two-fold increase in the percentage of PC-like cells after prolonged culturing in the presence of IL-21 (Fig. 3, B and D). Altogether, these data indicate that RIF1 deficiency promotes the *ex vivo* differentiation of activated B cells to PBs and PC-like cells.

RIF1 curtails plasma cell formation following immunization

We next investigated whether RIF1 influences the differentiation of activated B cells into PCs also *in vivo*. To this end, we analyzed the PC compartment of control and *Rif1*$^{F/F}$*Cd19*$^{Cre/+}$ mice immunized with the T-cell-dependent antigen 4-Hydroxy-3-nitrophenylacetyl hapten conjugated to Chicken Gamma Globulin (NP-CGG) (Fig. 4A). *Rif1*$^{F/F}$*Cd19*^{Cre} mice showed a consistent increase in the proportion of PCs (TACI^{+}CD138^{+}AA4.1^{+}MHCII^{-}) within the ASC population compared to controls in both spleen and bone marrow at earlier time points post-immunization (day 7 and 14 in the spleen and day 14 in the bone marrow) (Fig. 4B and S3). The phenotype was no longer observed in either compartment at later time points (day 28, Fig. 4B) nor in unimmunized mice (Fig. S4). These finding indicate that RIF1 deletion removes a physiological restraint imposed over the terminal differentiation of mature B cells, which, though concealed under steady-state conditions *in vivo*, the phenotype is readily detectable at the systemic level upon immunization.

Several recent studies have proposed that, besides SHM, B cell receptor (BCR) diversification *via* CSR can also influence the differentiation outcome of GC B cells (Gómez-Escolar et al. 2022; Kometani et al. 2013; Gitlin et al. 2016; King et al. 2021). Given the strict dependency of CSR on RIF1 (Chapman et al. 2013; Di Virgilio et al. 2013; Escribano-Díaz et al. 2013), it is tempting to speculate that the skewed differentiation potential of RIF1-deficient B cells might represent an indirect consequence of altered BCR signaling or GC recruitment caused by defective isotype switching. However, the *ex vivo* recapitulation of the differentiation phenotype (Fig. 3A), in the absence of BCR engagement and physiological microenvironmental cues, argues against this possibility and in favor of a cell-intrinsic role of RIF1 in shaping B cell identity during late differentiation.

RIF1 counteracts the premature repression of BLIMP1 target genes

To uncover the mechanism underlying RIF1 ability to restrain terminal B cell differentiation, we first monitored the genome-wide occupancy of RIF1 in activated B cells from *Rif1*$^{FH/FH}$ mice under the same stimulation conditions employed for the *ex vivo* transcriptional analyses (Fig. 5A, (Malzl et al. 2023)). *Rif1*$^{FH/FH}$ splenocytes express physiological levels of a knock-in 1×Flag-2×Hemagglutinin-tagged version of RIF1 (RIF1^{FH},(Cornacchia et al. 2012)) that supports its roles in mouse embryonic fibroblasts, embryonic stem cells, and B cells (Cornacchia et al. 2012; Foti et al. 2016; Di Virgilio et al. 2013). Interestingly, the vast majority of RIF1 peaks colocalized with promoters (56,4 %) and distal intergenic regions (25,4 %) (Fig. 5B). We next assessed the functional significance of both proximal- and distal-to-gene RIF1-binding events. We identified several categories of genes associated with the regulation of lymphocyte activation, function, and differentiation (Fig. S5A and Table S3). Altogether, these findings indicate that in activated B cells, RIF1 associates with cis-regulatory elements of genes involved in the modulation of the adaptive immune response.

We next explored the relationship of RIF1 with BLIMP1, the key transcriptional regulator of terminal B cell differentiation (Minnich et al. 2016; Malzl et al. 2023). To this end, we first assessed their relative genome occupancy by comparing RIF1 peaks (Fig. 5B) with BLIMP1-bound regions in activated B cells (see Supplemental Materials and Methods). We found that 1300 genomic regions (corresponding to 1144 genes) were co-occupied by the two factors (Fig. 5C), and they primarily comprised active genes (Fig. S5B), many of which are involved in lymphocyte activation and differentiation (Fig. S5C and Table S3). Since genome occupancy is

not indicative *per se* of a gene regulatory activity, we next asked whether RIF1 deficiency affects the transcriptional status of BLIMP1 targets, which are defined as BLIMP1-occupied genes that are either up- (repressed, 121 targets) or down- (activated, 93 targets) regulated following its ablation (Minnich et al. 2016). We found that several BLIMP1-activated genes were significantly up-regulated in *Rif1*$^{F/F}$*Cd19*$^{Cre/+}$ cells at 96 h post-activation (Fig. 5D), which is in agreement with the increased percentage of PBs in these cultures (Fig. 3A). More interestingly, BLIMP1-repressed targets were tendentially downregulated in the absence of RIF1 (Fig. 5D). The phenotype was evident not only at 96 h, but also at 72 h post-activation (Fig. 5D), before the physiological appearance of phenotypically-defined PBs (Scharer et al. 2018). Furthermore, a considerable portion of these genes is occupied by RIF1 in wild-type (*Rif1*$^{FH/FH}$) cells (Fig. S5D), which suggests a direct modulatory function. Altogether, these findings indicate that RIF1 supports the expression of several genes that are physiologically down-regulated by BLIMP1 as part of the transcriptional program promoting B cell differentiation into ASCs.

Collectively, our results support a model where RIF1 serves as a gatekeeper of B cell identity during terminal differentiation through its capacity to counteract the premature repression of BLIMP1 target genes following activation. This gatekeeping role has important implications for the pathological consequences of deregulated plasma cell generation. Whilst producing a diverse Ig-switched repertoire enables effective antibody-mediated responses, tight regulation and fine tuning of late B cell differentiation is essential to counteract the development of autoimmunity and PC-derived malignancies (Elkon and Casali 2008; Barwick et al. 2019; García-Sanz et al. 2016). Hence, by enabling *Igh* diversification *via* CSR while exerting a modulatory

231 function on PC differentiation, RIF1 integrates key requirements for the

232 establishment of protective humoral immunity.

Materials & Methods

Mice and derived primary cell cultures

Rif1$^{FH/FH}$ (Cornacchia et al. 2012), *Cd19*^{Cre} (Rickert et al. 1997) and *Rif1*$^{F/F}$*Cd19*$^{Cre/+}$ (Di Virgilio et al. 2013) mice were previously described and maintained on a C57BL/6 background. Mice were kept in a specific pathogen-free (SPF) barrier facility and all experiments were performed in compliance with the European Union (EU) directive 2010/63/EU, and in agreement with Landesamt für Gesundheit und Soziales directives (LAGeSo, Berlin, Germany). Mice of both genders were used for the experiments.

Resting B lymphocytes were isolated from mouse spleens using anti-CD43 MicroBeads (Miltenyi Biotec), and grown in RPMI 1640 medium (Life Technologies) supplemented with 10% fetal bovine serum (FBS, Sigma-Aldrich), 10 mM HEPES (Life Technologies), 1 mM Sodium Pyruvate (Life Technologies), 1X Antibiotic Antimycotic (Life Technologies), 2 mM L-Glutamine (Life Technologies), and 1X 2-Mercaptoethanol (Life Technologies) at 37 °C and 5% CO2 levels. Naïve B cells were activated by addition of 5-25 μg/ml LPS (Sigma-Aldrich) and 5 ng/ml of mouse recombinant IL-4 (Sigma-Aldrich) (L-I), or 5 μg/ml LPS, 10 ng/ml BAFF (PeproTech) and 2 ng/ml TGFβ (L-B-T), or 5 μg/ml LPS only (L).

RNA-Seq

For each RNA-Seq dataset, the analysis was performed on three mice per genotype. Splenocytes were cultured in LPS and IL-4 (LI), LPS, BAFF and TGFβ (LBT), or LPS (L), and cells were collected at the indicated time points by centrifugation. RNA was extracted with TRIzol (Invitrogen) according to manufacturer's instructions, and

ribosomal RNA was depleted using Ribo-Zero Gold rRNA Removal Kit (Illumina) for all datasets except for the RNA-Seq analysis in naïve versus L-I/L-B-T/L-activated splenocytes from WT mice (Fig. 1 and S1), for which RNase H (Epicentre) treatment was used. Libraries were prepared with TruSeq Stranded Total RNA Library Prep Kit Gold (Illumina), and run in one lane on a flow cell of NovaSeq 6000 SP (Illumina).

ChIP-Seq

ChIP-Seq for RIF1 in LPS and IL-4-stimulated splenocyte cultures was previously described (Malzl et al. 2023). H3K4me3 ChIP-Seq was performed in splenocytes activated with LPS and IL-4 for 72 h, and employed anti-H3K4me3 antibody (abcam, ab8580) for the ChIP part of the previously described protocol (Pavri et al. 2010). For H3K27me3 ChIP-Seq, we used H3K27me3 antibody (Cell Signalling, C36B11), and 2.5% human shared chromatin was spiked into all samples as an internal reference for normalization (Bonhoure et al. 2014).

B cell development and differentiation analyses

For analysis of CSR in *ex vivo* cultures, cell suspensions were stained with anti-IgG1-APC (BD Biosciences), anti-IgG3-Biotin and Streptavidin-APC (BD Biosciences), or anti-IgG2b-PE (BioLegend). For analysis of plasmablast differentiation *ex vivo*, isolated naïve splenic B cells were cultured at a density of 0,5 x 10^6 cells/ml in the presence of 25 μg/ml LPS and 5 ng/ml IL-4 and stained with anti-CD138 (BioLegend). For analysis of plasma cell-like differentiation *ex vivo*, the induced GC B (iGB) culture system was used as described before (Nojima et al. 2011; Haniuda and Kitamura 2019). Briefly, 40LB feeder cells (Balb/c 3T3 cell line expressing exogenous CD40-ligand (CD40L) and B-cell activating factor (BAFF))

were irradiated with 80 Gy and co-cultured with primary splenic B cells for 4 days in high glucose DMEM medium (Gibco) supplemented with 10% FBS, 10 mM HEPES, 1 mM Sodium Pyruvate, 1X Pen/Strep (Life Technologies), 1x MEM Non-Essential Amino Acids (Life Technologies), 2 mM L-Glutamine, 1X 2-Mercaptoethanol and 1 ng/ml IL-4 at 37 °C and 5% CO_2 levels. On day 4, cells were harvested, washed one time with PBS and re-plated in a newly irradiated 40LB feeder layer in the presence of 10 ng/ml IL-21 (PeproTech) for the next 4 days. For assessing CSR and plasma cell-like differentiation on day 4 and 8, 1 x 10^6 B cells were washed one time with FACS buffer (PBS supplemented with 1% FCS and 1 mM EDTA), blocked with TruStain fcX (BioLegend) for 10 min at 4° C and stained with the respective antibodies as stated above. 1 µg/ml of propidium iodide (PI) was used for live/dead cell staining.

For analysis of the plasma cell compartment *in vivo*, 8-14 week-old mice were sacrificed to isolate the spleen and tibia. Single cell suspensions were incubated for 2 min with ACK buffer (Gibco) for red blood cell lysis. For surface staining, 5-7 × 10^6 cells were first blocked with TruStain fcX for 10 min at 4 °C and then stained for CD138, CD267/ TACI (BD Pharmingen), MHC-II (Biolegend) and CD93/AA4.1 (Biolegend) 20 min at 4° C. Cells were resuspended in FACS buffer containing PI and analyzed. Immunization was performed by intraperitoneal injection of 100 µg of NP-CGG (Biosearch Technologies; ratio 10-20) precipitated in alum (Sigma).

All samples were acquired on a LSRFortessa cell analyzer (BD Biosciences).

Data availability

All RNA-Seq datasets reported in this study, and H3K4me3 and H3K27me3 ChIP-Seq data have been deposited in the GEO repository under accession number

GSE237560 (token for editor and reviewers: anqtcskkfbqxjel).The transcriptional signatures of activated B cells, PBs, and PCs have been defined using the corresponding (and naïve B cells for baseline comparison) RNA-Seq datasets from ((Minnich et al. 2016), GSE71698). RIF1 ChIP-Seq was previously reported ((Malzl et al. 2023), GSE228880). The BLIMP1-bound regions in activated B cells were defined based on the BLIMP1 Bio-ID dataset from ((Minnich et al. 2016), GSE71698). The lists of BLIMP1-activated and -repressed targets have been previously described (Minnich et al. 2016). Details of data analyses are described in the Supplemental Materials and Methods file.

Competing Interest Statement

The authors declare no competing interests.

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Author contributions: A.R. and E.K. conceived the project idea, designed and performed experiments; M.B.L. and V.D.B prepared the RNA-seq libraries; A.R. analyzed all high-throughput sequencing data; R.A. contributed to the sequencing data analysis; R.P. engaged in active discussions on the study; M.D.V. secured the funding for the project, supervised all aspects of the study, and wrote the manuscript; A.R. and E.K. reviewed and edited the manuscript.

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Supplemental Material

Supplemental_Fig_S1.pdf

Stimulation-dependent clustering of B cell transcriptomics profiles after *ex vivo* activation. Related to Figure 1.

Supplemental_Fig_S2.pdf

RIF1-deficiency alters the transcriptional landscape of activated B cells. Related to Figure 2.

Supplemental_Fig_S3.pdf

***Rif1*$^{F/F}$*Cd19*$^{Cre/+}$ mice exhibit physiological numbers of ASCs after immunization.** Related to Figure 4.

Supplemental_Fig_S4.pdf

RIF1 ablation does not result in detectable changes of the plasma cell compartment in steady state condition. Related to Figure 4.

Supplemental_Fig_S5.pdf

RIF1 and BLIMP1 co-occupied genomic regions comprise active genes involved in lymphocyte activation and differentiation. Related to Figure 5.

Supplemental_Table_S1.xlsx

Pairwise comparison of differentially regulated genes in control (*Cd19*$^{Cre/+}$) *versus Rif1*$^{F/F}$*Cd19*$^{Cre/+}$ splenocytes. Related to Figures 2 and S2.

Supplemental_Table_S2.xlsx

Lists of genes in the PB and PC transcriptional signatures that are differentially regulated in *Rif1*$^{F/F}$*Cd19*$^{Cre/+}$ activated B cells. Related to Figures 2 and S2.

Supplemental_Table_S3.xlsx

Lists of RIF1- and RIF1&BLIMP1-bound genes in the top GREAT gene ontology enrichment categories. Related to Figure S5.

Supplemental_Table_S4.xlsx

Lists of RIF1&BLIMP1 target genes. Related to Figure S5.

Supplemental_Materials_&_Methods.pdf

Data analysis and Softwares.

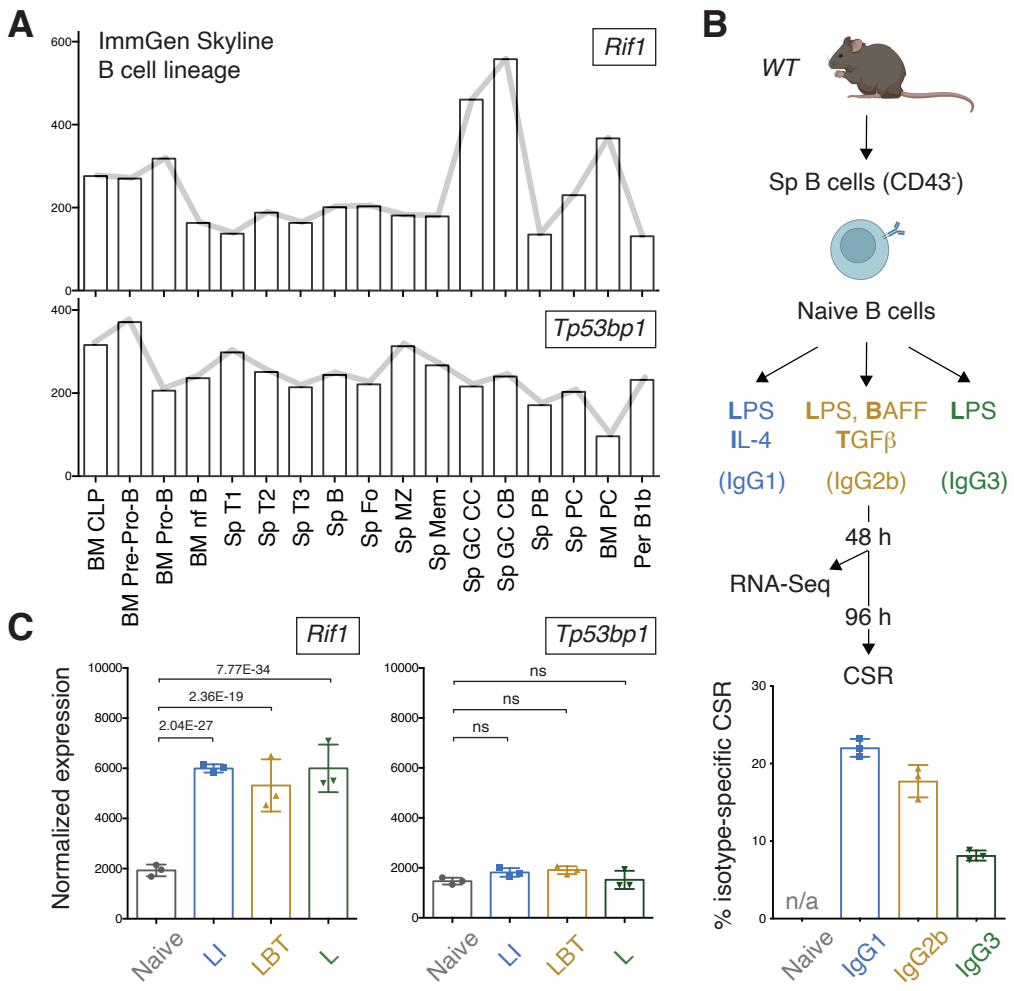

Figure 1. *Rif1* expression is dynamically regulated during late B cell differentiation. (A) Expression of *Rif1* (top) and *Tp53bp1* (bottom) genes across B cell lineage developmental stages as determined by the Immunological Genome Project (ImmGen) Skyline RNA-Seq analysis. BM: bone marrow; CLP: common lymphoid progenitor; nf: newly-formed; Sp: splenic; Fo: follicular; MZ: marginal zone; Mem: memory; GC: germinal center; CC: centrocytes; CB: centroblasts; PB: plasmablasts; PC: plasma cells; Per B1b: peritoneal B1b. (B) Top: Schematic representation of gene expression analysis in naïve B cells isolated from mouse spleens and stimulated *ex vivo* with LPS and IL-4 (LI cocktail), LPS, BAFF and TGFβ (LBT), or LPS only (L). Bottom: CSR efficiency to the corresponding isotype for each of the primary B cell cultures employed in the RNA-Seq analysis (n = 3 mice per stimulation condition). n/a: not applicable. (C) Expression of *Rif1* (left) and *Tp53bp1* (right) genes in naïve and LI/LBT/L-stimulated B cells. Expression values were normalized by DESeq2 and the adjusted p-value of significant differences between samples is indicated. ns: not significant.

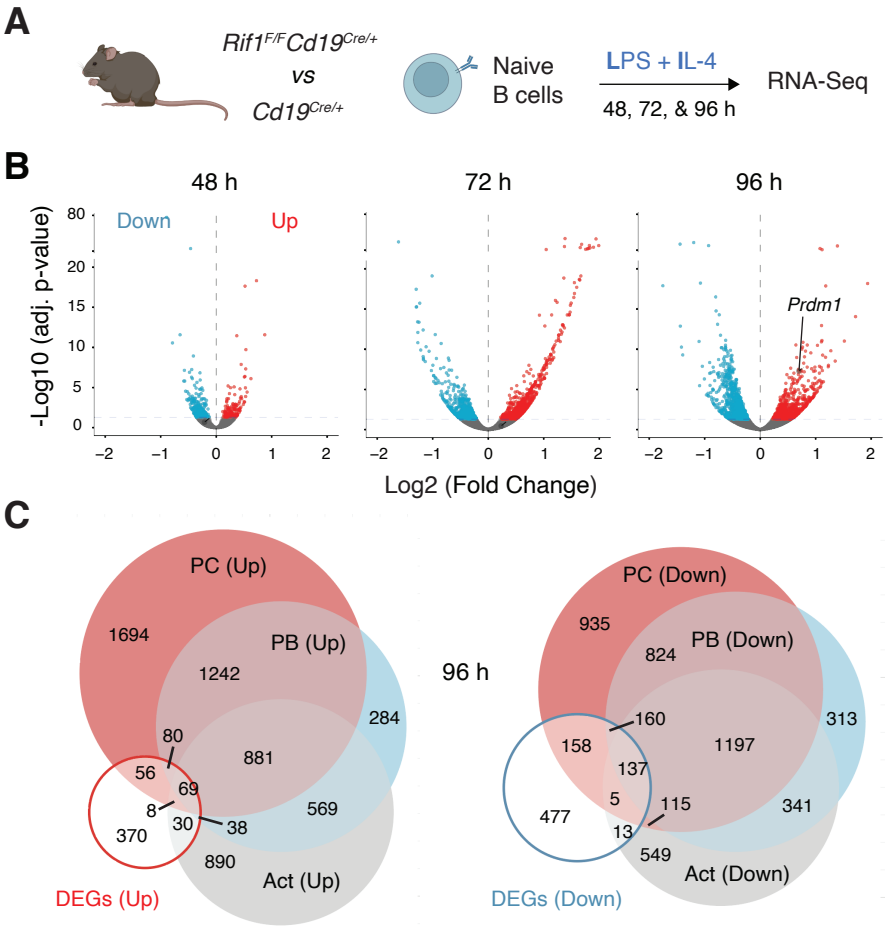

Figure 2. RIF1 deficiency skews the transcriptional profile of activated B cells towards ASCs. (A) Schematic representation of gene expression analysis in naïve B cells isolated from *Cd19*$^{Cre/+}$ and *Rif1*$^{F/F}$*Cd19*$^{Cre/+}$ mouse spleens and stimulated *ex vivo* with LI for 48, 72, and 96 h. For the 48 h time point, the analysis was performed also on LBT-stimulated cultures. (B) Volcano plots displaying differentially expressed genes between control and RIF1-deficient splenocytes. The blue and red dots represent transcripts down- and up-regulated (adjusted p-value <= 0.05, blue horizontal dotted line), respectively, in *Rif1*$^{F/F}$*Cd19*$^{Cre/+}$ cells. (C) Venn diagrams depicting the overlaps between genes up- (left) and down- (right) regulated in RIF1-deficient splenocytes at 96 h post-activation and the corresponding up-and down-regulated (over naïve B cells) categories in the activated (Act) B cell, PB, and PC transcriptional signatures (Minnich et al. 2016).

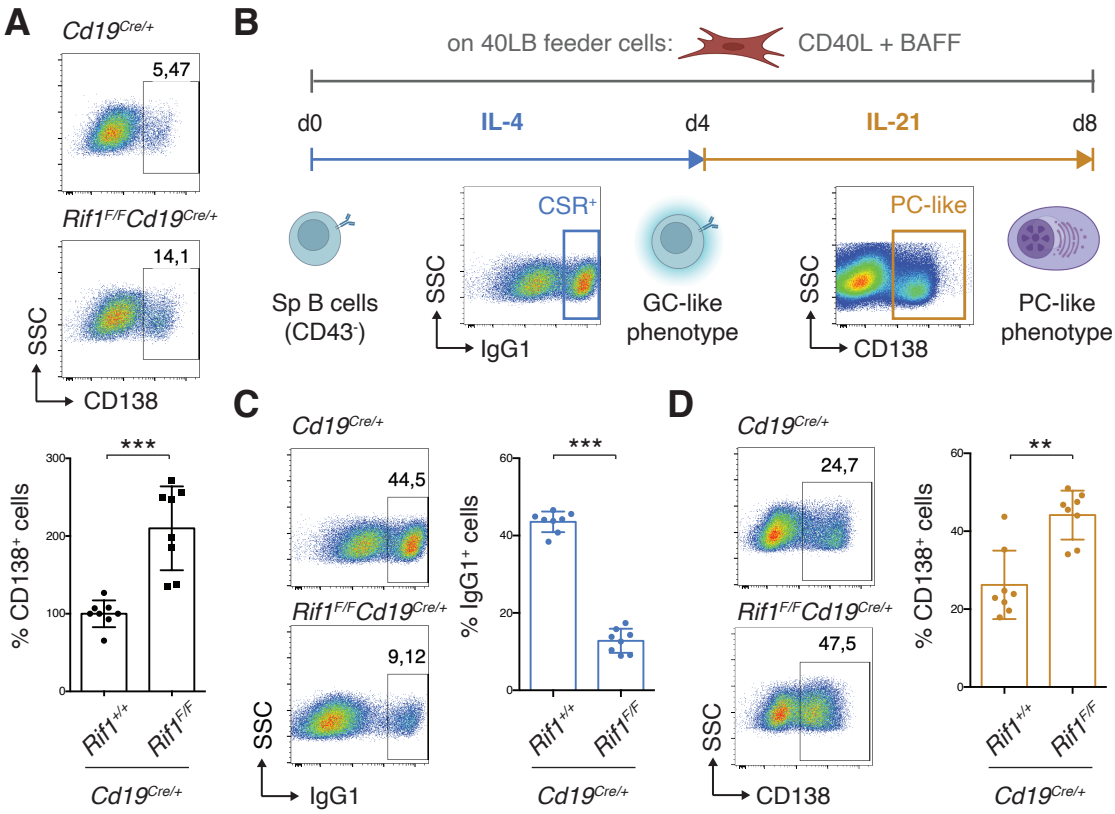

Figure 3. *Ex vivo* differentiation of activated B cells to PBs and PC-like cells is increased in the absence of RIF1. (A) Top: Representative flow cytometry plots measuring percentage of plasmablasts (CD138+) in splenocyte cultures of the indicated genotypes 96 h after activation with LI. Bottom: Summary graph for five independent experiments (n = eight mice per genotype), with % of CD138+ cells within each experiment normalized to the average of control mice (*Cd19*$^{Cre/+}$), which was set to 100%. (B) Schematic representation of the iGB (induced germinal center (GC) phenotype B) cell culture system for the *ex vivo* differentiation of splenic naïve B cells to GC- and plasma cell-like cells. CD40L: CD40 ligand; d: day; Sp: splenic; CSR+: class switched cells; PC: plasma cell. (C-D) Left: Representative flow cytometry plots measuring CSR to IgG1 (C) and percentage of plasmablasts (CD138+) (D) in splenocytes cultures of the indicated genotypes at day 4 (C) and 8 (D), respectively, of the iGB cell culture system shown in panel B. Right: Summary graphs for five independent experiments (n = eight mice per genotype). Significance in panels A, C and D was calculated with the Mann–Whitney U test, and error bars represent SD. ** = $p \leq 0.01$; *** = $p \leq 0.001$.

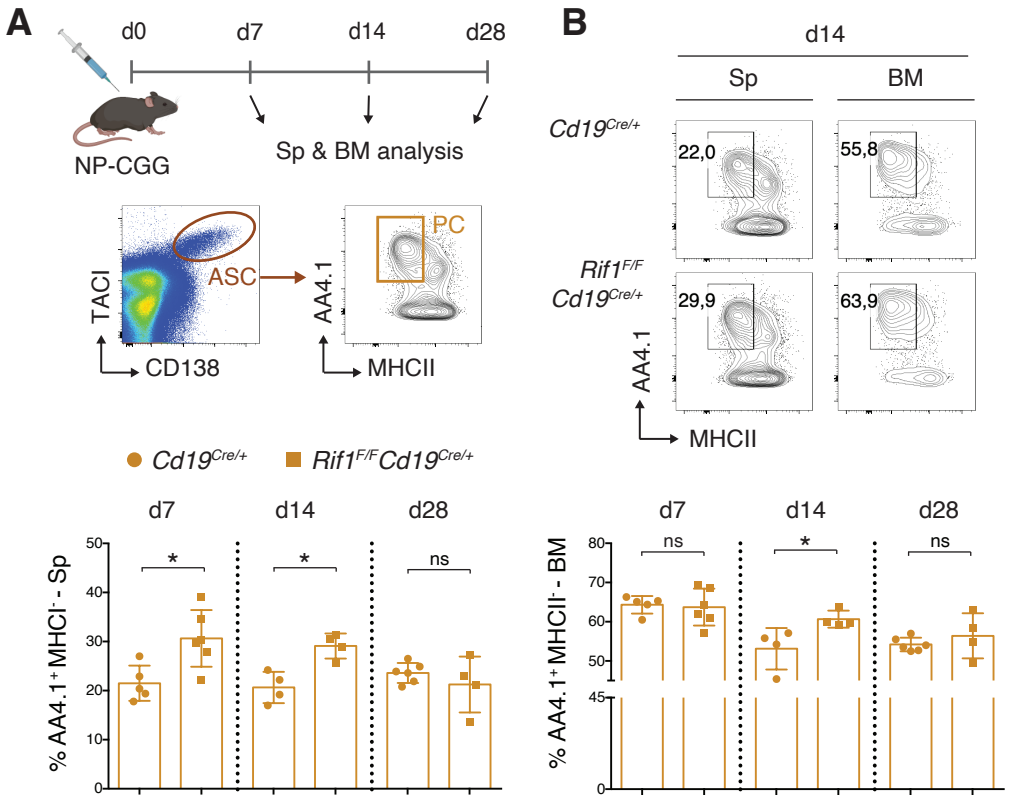

Figure 4. Ablation of RIF1 enhances plasma cell formation after immunization. (A) Schematic representation of the NP-CGG immunization protocol and gating strategy employed for the phenotypic analysis of the plasma cell compartment. d: day; NP-CGG: 4-hydroxy-3-nitrophenylacetyl hapten conjugated to Chicken Gamma Globulin; Sp: spleen; BM: bone marrow; ASC: antibody secreting cell; PC: plasma cell. (B) Top: Representative flow cytometry plots measuring percentage of plasma cells in spleens and bone marrows of mice of the indicated genotypes at day 14 after immunization. Bottom: Graphs summarizing the percentage of plasma cells in spleens (left) and bone marrows (right) for >= four mice per genotype and time point. Significance in panel B was calculated with the Mann–Whitney U test, and error bars represent SD. ns: not significant; * = $p \leq 0.05$.

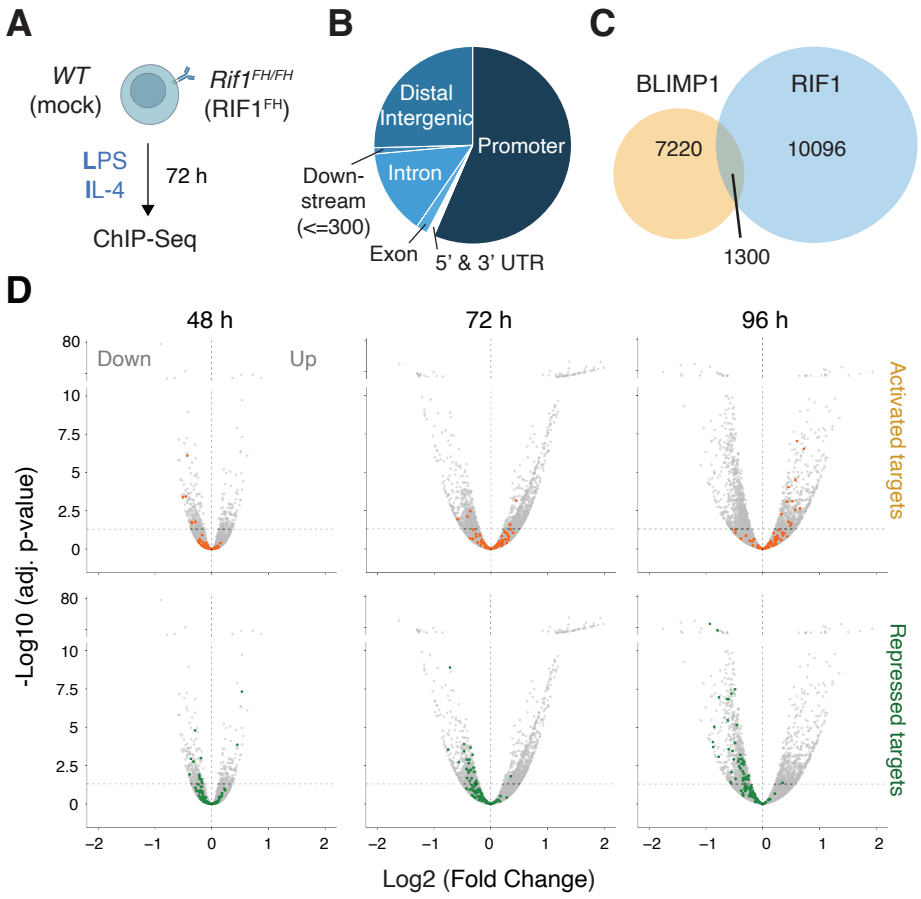

Figure 5. RIF1 counteracts the premature repression of BLIMP1 target genes. (A) Schematic representation of the ChIP-Seq analysis in mature B cells isolated from spleens of *Rif1*$^{FH/FH}$ mice and stimulated *ex vivo* with LI. (B) Genomic distribution of RIF1-occupied annotated regions. (C) Venn diagram depicting the overlap between RIF1- and BLIMP1-bound genomic regions in activated B cells. (D) Volcano plots displaying BLIMP1-activated (in orange, top) and -repressed (in green, bottom) target genes among the transcripts (in grey both up- and down-regulated) identified in the *Cd19*$^{Cre/+}$ *versus* *Rif1*$^{F/F}$*Cd19*$^{Cre/+}$ transcriptome analysis shown in Fig. 2. The horizontal dotted line in the plots denotes the adjusted p-value of 0.05.