Arginine methylation of the B cell antigen receptor promotes differentiation

Simona Infantino,1,3 Beate Benz,1,3 Tanja Waldmann,3 Manfred Jung,2 Robert Schneider,3 and Michael Reth1,3

The BCR is composed of the membrane-bound Ig molecule and the Igα/Igβ heterodimer signaling subunits. The amino acid sequence of the cytosolic tail of Igα is highly conserved and contains an immunoreceptor tyrosine-based activation motif (ITAM; Reth, 1989). The ITAM tyrosines of Igα and Igβ control the diverse signaling output of the BCR (Kraus et al., 2004; Gazumyan et al., 2006). Upon phosphorylation, the two tyrosines of the ITAM are bound by the protein tyrosine kinase (PTK) Syk (Grucza et al., 2006). Upon phosphorylation, the two tyrosines of the ITAM are bound by the protein tyrosine kinase (PTK) Syk (Grucza et al., 2006). SYK provides a survival signal that uses the PI-3 kinase (PI3K) pathway (Srinivasan et al., 2009). In addition, the BCR provides a survival signal that uses the PI-3 kinase (PI3K) pathway (Srinivasan et al., 2009). Recent findings suggest that Foxo family transcription factors also induce differentiation of pre-B cells, whereas signals from PI3K negatively control this process by causing the degradation of Foxo proteins (Amin and Schlissel, 2008; Herzog et al., 2008). Interestingly, protein arginine methyltransferase 1 (PRMT1) was found to methylate the Foxo1 protein, thereby inhibiting its phosphorylation and subsequent degradation (Yamagata et al., 2008).

PRMTs are enzymes that catalyze the transfer of a methyl group from S-adenosyl-methionine to the nitrogen atoms of the arginine guanidinium group (Gary and Clarke, 1998). To date, 12 different PRMTs have been identified (Bedford, 2007; Bedford and Clarke, 2009). Depending on their ability to produce either asymmetric or symmetric dimethylated arginines, they are designated as type I or II enzymes, respectively (Gary and Clarke, 1998). PRMTs not only methylate histones in the nucleus but also substrates in the cytosol, some of which show altered signaling behavior upon methylation (Mowen et al., 2004; Blanchet et al., 2005; Lawson et al., 2007). So far, however, arginine methylation of membrane-bound components has not been described in eukaryotes. We noticed that the Igα cytoplasmic tail contains a conserved arginine (R198) followed by a glycine (G199), thus resembling the sequence context (R-G) found in PRMT substrate proteins (Najbauer et al., 1993; Blanchet et al., 2006; Bedford, 2007). We show in this paper that R198 of Igα is constitutively methylated by PRMT1 and that this modification inhibits PI3K signaling while promoting signals leading to B cell differentiation.

Abbreviations used: GST, glutathione S-transferase; HA, hemagglutinin; ITAM, immunoreceptor tyrosine-based activation motif; NIP, 4-hydroxy-5-iodo-3-nitrophenyl acetyl; PI3K, PI-3 kinase; PLA, proximity ligation assay; PRMT, protein arginine methyltransferase; PTK, protein tyrosine kinase; siRNA, small interfering RNA.

The BCR provides a survival signal that uses the PI-3 kinase (PI3K) pathway (Srinivasan et al., 2009). Recent findings suggest that Foxo family transcription factors also induce differentiation of pre-B cells, whereas signals from PI3K negatively control this process by causing the degradation of Foxo proteins (Amin and Schlissel, 2008; Herzog et al., 2008). Interestingly, protein arginine methyltransferase 1 (PRMT1) was found to methylate the Foxo1 protein, thereby inhibiting its phosphorylation and subsequent degradation (Yamagata et al., 2008).

PRMTs are enzymes that catalyze the transfer of a methyl group from S-adenosyl-methionine to the nitrogen atoms of the arginine guanidinium group (Gary and Clarke, 1998). To date, 12 different PRMTs have been identified (Bedford, 2007; Bedford and Clarke, 2009). Depending on their ability to produce either asymmetric or symmetric dimethylated arginines, they are designated as type I or II enzymes, respectively (Gary and Clarke, 1998). PRMTs not only methylate histones in the nucleus but also substrates in the cytosol, some of which show altered signaling behavior upon methylation (Mowen et al., 2004; Blanchet et al., 2005; Lawson et al., 2007). So far, however, arginine methylation of membrane-bound components has not been described in eukaryotes. We noticed that the Igα cytoplasmic tail contains a conserved arginine (R198) followed by a glycine (G199), thus resembling the sequence context (R-G) found in PRMT substrate proteins (Najbauer et al., 1993; Blanchet et al., 2006; Bedford, 2007). We show in this paper that R198 of Igα is constitutively methylated by PRMT1 and that this modification inhibits PI3K signaling while promoting signals leading to B cell differentiation.

Abbreviations used: GST, glutathione S-transferase; HA, hemagglutinin; ITAM, immunoreceptor tyrosine-based activation motif; NIP, 4-hydroxy-5-iodo-3-nitrophenyl acetyl; PI3K, PI-3 kinase; PLA, proximity ligation assay; PRMT, protein arginine methyltransferase; PTK, protein tyrosine kinase; siRNA, small interfering RNA.
RESULTS AND DISCUSSION

Igα cytoplasmic tail is methylated by PRMT1

A comparison of the Igα tail sequences from several mammals (mouse, human, and bovine) reveals a conserved arginine residue (R198) situated in close proximity to the last ITAM tyrosine (Y193; Fig. 1 A). The emerging role of arginine methylation in lymphocytes prompted us to investigate whether Igα might be modified by PRMTs.

To test for this, we used a radioactive in vitro methylation assay using the immunopurified, hemagglutinin (HA)-tagged enzymes PRMT1, 3, 5, and 6 with either glutathione S-transferase (GST) or GST-Igα (mouse cytoplasmic domain) as substrates. After a 1-h reaction, only PRMT1 incorporated methyl groups into proteins of the reaction mix, including a protein of the size of GST-Igα (Fig. 1 B, top, lane 4, asterisk). Equal loading was confirmed with anti-GST and anti-HA antibodies (Fig. 1 B, middle and bottom), and the activity of all purified PRMT enzymes was verified using histone H2A as substrate (Fig. 1 C). This analysis showed that the cytoplasmic tail of Igα is a specific substrate of PRMT1 in vitro.

To verify that R198 is the target of PRMT1, we replaced R198 in the tail of Igα with a lysine (K198). The analysis of GST-Igα fusion proteins with either WT or K198 mutant tails in the radioactive in vitro methylation assay showed that only the GST-Igα WT but not the K198 mutant is methylated by PRMT1 (Fig. 1 D, top). Therefore, R198 is the only PRMT1 target site in the Igα tail sequence.

To test whether Igα is methylated in B cells, we used ex vivo–cultured pro–B cells derived from the BM of mb-1−/−/B1-8 knockin mice. Because of the deletion of the mb-1 gene, these pro–B cells (Igα KO) do not produce Igα but express the B1-8 H chain from a V_{H}DJ_{H} knockin allele (Pelanda et al., 2002). Transfection of these pro–B cells with retroviral vectors encoding a λ L chain and a flag-tagged Igα results in the expression of a BCR that binds to the hapten 4-hydroxy-5-iodo-3-nitrophenyl acetyl (NIP; Reth et al., 1978; Meixlsperger et al., 2007).

To monitor arginine methylation of Igα more directly, we generated an anti–R<sup>ω</sup>-Igα antibody that specifically recognizes the monomethylated form of R198 (Fig. S1). With this antibody, we detected Igα methylation in Igα KO B cells stably expressing Igα WT (Fig. 2 A, top, lane 1). The R198 methylation was prevented by treatment of the B cells with the PRMT1 inhibitor 35605 (Fig. 2 A, top, lane 2; Spannhoff et al., 2007). To obtain more direct evidence that PRMT1 knockdown is sufficient to prevent R198 methylation, we performed a PRMT1 knockdown experiment in HEK293 cells stably expressing a CD8-Igα chimera containing the WT but not the K198 mutant tail sequences (Fig. 2 B). The parallel analysis of R198 methylation revealed that Igα is methylated in all BCR<sup>+</sup> cell subsets but not in pre–B cell subsets (Fig. 2 C, top). The parallel analysis of R198 methylation revealed that Igα is methylated in all BCR<sup>+</sup> cell subsets but not in pre–B cell subsets (Fig. 2 C, top).

Using sorted B cell populations from the BM and spleen, we found that PRMT1 is expressed in all B cell subsets examined with the highest amount in pre–B cells (Fig. 2 C, top). The parallel analysis of R198 methylation revealed that Igα is methylated in all BCR<sup>+</sup> cell subsets but not in pre–B cell subsets (Fig. 2 C, top).
cells (Fig. 2 D, top). It has been reported that the pre-BCR
constitutively produces an autonomous ligand-independent
signal (Meixlsperger et al., 2007). The finding that Igα meth-
ylation was detected in B cells but not in pre-B cells suggests
that the R198 methylation has an inhibitory role.

BCR activation alters Igα arginine methylation
To investigate whether the tail of Igα is also methylated upon
B cell activation, we reconstituted Igα KO cells with both
IgαWT or IgαK198 mutant and L chain. A FACS analysis verified
that transfectants producing either IgαWT or the
IgαK198 mutant express similar amounts of BCR on the sur-
face (Fig. S2, top).

The transfected B cells were cultured for 3 h with L-
[methyl-3H]methionine in the presence of protein synthesis
inhibitors. The cells were then either left unstimulated or
stimulated for different times (2.5–30 min) with NIP-BSA
(Fig. 2 E). The Igα proteins in the total cellular lysate of these
cells were immunopurified with anti-flag antibodies and
analyzed for methyl-3H incorporation by autoradiography
(Fig. 2 E, top). Radioactive methyl groups were predominantly
incorporated into IgαWT and to a much lesser extent into the
IgαK198 mutant. The weak radioactivity of the IgαK198
mutant may be caused by an incomplete inhibition of protein
synthesis that resulted in some incorporation of [3H]methionine
in newly synthesized Igα. Interestingly, the methylation of
IgαWT was strongest in nonstimulated B cells, declined 2.5
and 5 min after BCR ligation, and reappeared after 30 min of
exposure of B cells to NIP-BSA (Fig. 2 E, top). We controlled
for similar amounts of precipitated Igα protein with an anti-
flag antibody (Fig. 2 E, middle). Furthermore, similar amounts
of methylated proteins in the total cellular lysates of the cells
demonstrated equal 3H incorporation (Fig. 2 E, bottom). This
is in line with equal expression of PRMT1 in untransfected as
well as in Igα-expressing B cells (Fig. S3, top). The time-
course experiment was then repeated using the specific anti–
Rm-Igα antibody to detect R198 methylation in the total
cellular lysate of WT or mutant Igα-producing B cells. Again,
Arginine methylation modifies BCR signaling | Infantino et al.

Igα R198 methylation was high in resting B cells, reduced 2.5 and 5 min after BCR activation, and reappeared at later time points (Fig. 2 F, top). These data, together with the absence of Igα methylation in pre–B cells, suggest that R198 methylation is a feature of the BCR on resting B cells.

To directly test for Igα–PRMT1 interaction, we used the Duolink in situ proximity ligation assay (PLA). Intriguingly, PRMT1 appeared to be most strongly associated with Igα before activation (Fig. 3 A, top right). At 2.5 min after BCR activation, PRMT1 partially dissociated from Igα to further reassociate with it at later time point (Fig. 3 A, bottom). The time course of Igα–PRMT1 interaction correlates well with the kinetics of Igα methylation. No signal was visible in the Igα KO control cells (Fig. 3 A, top left). The number of dots per cell were counted and plotted with the relative statistical calculations (Fig. 3 B). The specificity of this assay was also confirmed by analyzing the Igα–Syk interaction, which occurred only after BCR activation (Fig. 3, C and D).

**Arginine methylation of Igα modulates BCR activation**

To examine the role of Igα arginine methylation in BCR signaling, we compared the behavior of B cells expressing either IgαWT or the IgαK198 mutant. One of the earliest events after the engagement of the BCR is the activation of the PTKs Syk and Lyn and the phosphorylation of several PTK substrates, including Igα. A time-course experiment monitoring tyrosine phosphorylation after stimulation of the BCR with NIP-BSA did not show any major difference between B cells expressing WT or mutated Igα (Fig. 4 A, top). However, by using site-specific antibodies detecting either the phosphorylation of Y630 in the C-terminal tail of Syk (Kulathu et al., 2008) or phosphorylation of S473 in the serine/threonine kinase AKT/PKB, we found that both proteins are more strongly phosphorylated in B cells expressing a BCR with the IgαK198 mutant than in those carrying IgαWT (Fig. 4 B, top and middle). Interestingly, after 30 min of BCR stimulation, the phosphorylation of these proteins declines, whereas arginine methylation of Igα reappears (compare Fig. 2 E, Fig. 2 F, and Fig. 4 B). This inverse correlation between phosphorylation and arginine methylation suggests that the methylation of R198 of Igα plays a negative regulatory role for B cell activation.

The R198 is situated only 5 aa after the last ITAM tyrosine (Y193), and it is feasible that methylation of R198 may interfere with the binding of Syk to the BCR. To examine this, we purified the BCR containing either IgαWT or IgαK198 mutant at different time points after B cell activation and found that 2–5 min after stimulation, Syk is more...
strongly associated with the mutant than with the WT BCR (Fig. 4 C, top). These data support the notion that the methylation of R198 can modulate BCR signaling.

**Igα arginine methylation negatively controls Ca^{2+} signaling**

B cells respond to BCR ligation with a rapid increase in the intracellular Ca^{2+} concentration (Scharenberg et al., 2007). We compared the Ca^{2+} response of NIP-BSA–stimulated B cells expressing either WT or an IgαK198 mutant BCR. The Ca^{2+} influx was clearly higher in the B cells with the mutant BCR (Fig. 5 A). The same was true for cells expressing a mutant pre-BCR and stimulated with anti-IgM antibodies (Fig. S2, bottom). The increased B cell response could be caused by the R→K198 mutation itself or by the absence of Igα methylation. To test this, we stimulated cells expressing the WT BCR with NIP-BSA in the absence or presence of the PRMT1 inhibitor 35605 and monitored the calcium flux of the stimulated B cells. Interestingly, the inhibition of PRMT1 in stimulated cells expressing IgαWT resulted in a calcium response increased to a level similar to that seen in IgαK198 mutant B cells (Fig. 5 B). This finding indicates that it is the absence of methylation and not the mutation of Igα per se that increases the Ca^{2+} response in mutant B cells. Furthermore, when the PRMT1 inhibitor was applied to B cells expressing the IgαK198 mutant, no further augmentation in calcium flux was observed upon stimulation (Fig. 5 C), suggesting that the methylation of Igα rather than that of other PRMT1 substrates controls the intensity of the Ca^{2+} signal.

**Igα arginine methylation supports B cell differentiation**

The cytokine IL-7 is an important growth factor for mouse pre–B cells. The removal of IL-7 from pre–B cell cultures results in growth arrest of the pre–B cells and their increased differentiation, as indicated by L chain gene (κ followed by λ) assembly and the expression of a BCR on the surface of these cells (Rolink et al., 1991; Flemming et al., 2003). By comparing the amount of BCR^{+} cells generated after withdrawal of IL-7 from pre–B cell cultures expressing either IgαWT or the IgαK198 mutant, we noticed that the latter cells display a partial block in B cell differentiation (Fig. 5 E). 5 d after IL-7 removal, the IgαWT cultures contained 14% of BCR^{+} cells, whereas parallel cultures of mutant pre–B cells contained only 5.5% BCR^{+} cells (Fig. 5 E, bottom; and Fig. S4 A). To test whether arginine methylation mediated by PRMT1 was...
programs. Recently, it was discovered that Foxo family transcription factors promote the differentiation of pre–B cells and that signals processed through Syk and the PI3K pathways counteract this activity by degrading Foxo proteins (Amin and Schlissel, 2008; Herzog et al., 2008). Our finding that the R→K198 mutation increases Syk and PI3K signaling of the BCR and reduces the differentiation signal of the pre-BCR is in line with these data.

Igα arginine methylation appears to dampen signals from the BCR. In pre–B cells, Igα methylation is absent and the pre-BCR signals constitutively. Because receptor editing or B cell deletion removes cells with autoreactive BCR (Nemazee and Bürki, 1989; Gay et al., 1993), it is feasible that stronger signaling from BCR lacking Igα arginine methylation could also lead to negative selection. This may explain why the development of pre–B cells carrying IgαK198 mutant is impaired.

Finally, the dynamic changes in arginine methylation of Igα we detected after BCR stimulation suggest that not only arginine methylases but also arginine demethylases might modulate B cell activation. It is feasible that upon activation, the dissociation of PRMT1 from the BCR allows the recruitment of an arginine demethylase. Indeed, the Igα–PRMT1 interaction corresponds to the kinetics of required for efficient B cell differentiation, we cultured Igα WT pre–B cells for 4 d without IL-7 in the presence of different doses of the PRMT1 inhibitor 35605 (Fig. 5 F; and Fig. S4 B). At the highest dose of inhibitor, the number of BCR+ cells was reduced fivefold.

To test the in vivo function of R198 in B cell development, we reconstituted pro–B cells derived from Igα KO mice with an expression vector either for GFP, IgαWT-IRES-GFP, or IgαK198-IRES-GFP. The cells were sorted for GFP expression and transferred into RAG-2−/− mice. The developing B cells were analyzed 10 d later. In the spleen, most of the pre–B cells expressing WT Igα developed into BCR+ cells (67.7% IgM+), whereas pre–B cells carrying IgαK198 produced fewer IgM+ cells (19.7%; Fig. 6 A). Similarly, in the BM, although the majority of WT Igα-expressing pre–B cells became IgM+, only a few of the mutant cells developed into IgM+ cells (Fig. 6 B). In comparison to WT cells, a higher amount of IgαK198-expressing cells was found in the BM (Fig. 6 C, right). In the spleen, this situation was reversed (Fig. 6 C, left). This finding shows that Igα methylation is important for regulating B cell differentiation.

The expression of a functional pre-BCR is required for both the proliferation and the differentiation of pre–B cells. Thus, signals from the same receptor result in opposing cellular responses. Recently, it was discovered that Foxo family transcription factors promote the differentiation of pre–B cells and that signals processed through Syk and the PI3K pathways counteract this activity by degrading Foxo proteins (Amin and Schlissel, 2008; Herzog et al., 2008). Our finding that the R→K198 mutation increases Syk and PI3K signaling of the BCR and reduces the differentiation signal of the pre-BCR is in line with these data.

Igα arginine methylation appears to dampen signals from the BCR. In pre–B cells, Igα methylation is absent and the pre-BCR signals constitutively. Because receptor editing or B cell deletion removes cells with autoreactive BCR (Nemazee and Bürki, 1989; Gay et al., 1993), it is feasible that stronger signaling from BCR lacking Igα arginine methylation could also lead to negative selection. This may explain why the development of pre–B cells carrying IgαK198 mutant is impaired.

Finally, the dynamic changes in arginine methylation of Igα we detected after BCR stimulation suggest that not only arginine methylases but also arginine demethylases might modulate B cell activation. It is feasible that upon activation, the dissociation of PRMT1 from the BCR allows the recruitment of an arginine demethylase. Indeed, the Igα–PRMT1 interaction corresponds to the kinetics of required for efficient B cell differentiation, we cultured Igα WT pre–B cells for 4 d without IL-7 in the presence of different doses of the PRMT1 inhibitor 35605 (Fig. 5 F; and Fig. S4 B). At the highest dose of inhibitor, the number of BCR+ cells was reduced fivefold.

To test the in vivo function of R198 in B cell development, we reconstituted pro–B cells derived from Igα KO mice with an expression vector either for GFP, IgαWT-IRES-GFP, or IgαK198-IRES-GFP. The cells were sorted for GFP expression and transferred into RAG-2−/− mice. The developing B cells were analyzed 10 d later. In the spleen, most of the pre–B cells expressing WT Igα developed into BCR+ cells (67.7% IgM+), whereas pre–B cells carrying IgαK198 produced fewer IgM+ cells (19.7%; Fig. 6 A). Similarly, in the BM, although the majority of WT Igα-expressing pre–B cells became IgM+, only a few of the mutant cells developed into IgM+ cells (Fig. 6 B). In comparison to WT cells, a higher amount of IgαK198-expressing cells was found in the BM (Fig. 6 C, right). In the spleen, this situation was reversed (Fig. 6 C, left). This finding shows that Igα methylation is important for regulating B cell differentiation.

The expression of a functional pre-BCR is required for both the proliferation and the differentiation of pre–B cells. Thus, signals from the same receptor result in opposing cellular
Igα methylation. The identification and characterization of an arginine demethylase is likely to shed light on the regulation of BCR signaling.

MATERIALS AND METHODS

Mice. RAG-2<sup>−/−</sup>/γ<sup>−/−</sup> mice (Colucci et al., 1999) were used for the in vivo differentiation assay. Pro–B cells derived from the mb-1<sup>−/−</sup>/B1-8 knockin mice were retrovirally transduced with the respective vectors and injected intravenously into RAG-2<sup>−/−</sup>/γ<sup>−/−</sup> mice. 10 d later, mice were sacrificed by the Regierungspräsidium Freiburg. In vivo differentiation assay. Pro–B cells derived from the mb-1<sup>−/−</sup>/B1-8 knockin, and RAG-2<sup>−/−</sup>/γ<sup>−/−</sup> mice were bred at the animal facility of the Max-Planck-Institute for Immunobiology. Animal experiments were performed as approved by the Regierungspräsidium Freiburg.

Cell culture, transfection, and retroviral transduction. The pro–B cell line was established from mb-1<sup>−/−</sup>/B1-8 knockin BM cells cultured in Iscove’s medium containing 10% heat-inactivated FCS (PAN Biotech GmbH), 100 U/ml penicillin/streptomycin (Invitrogen), 50 µM 2-mercaptoethanol (EMD), and 0.5 ng/ml IL-7 derived from the supernatant of a J558L cell line transfected with a vector encoding mouse IL-7. Retroviruses (pMOWS-IRES-CD8 [Hertzog and Jumaa, 2007] and pMOWS-IRES-GFP, pMIG-IRES-GFP, pMIG-flag-Igα-IRES-GFP, pMIG-flag-Igα-IRES-GFP, and pMOWS-x1 [Meiselberger et al., 2007]) were generated by calcium chloride transfection of the Phoenix retroviral producer cell line. Supernatants containing retroviruses were harvested after 2 d. Viral infection of 2 × 10<sup>5</sup> pro–B cells was performed by the addition of 500 µl of supernatant followed by centrifugation at 1,800 rpm for 3 h at 37°C. Cells were expanded and sorted based on CD8 or GFP expression. λ1 expression was selected with 1 µg/ml puromycin. The pcDNA3.1-PRMT plasmids were used to transfect HEK293 cells with the calcium phosphate method and were further selected in medium containing G418.

Plasmids. A cDNA encoding an N-terminal flag-tag mouse Igα (Rolli et al., 2002) was inserted into pMOWS-IRES-CD8. The R198K mutation was introduced by sequential PCR steps. PCR fragments were cloned into a DraII/Xhol-digested pD-flag-Igα plasmid and subsequently transferred into pMOWS-IRES-CD8 or pMIG-IRES-GFP. The plasmids pRp261 and pRp261-Igα were used to generate the recombinant proteins GST and GST-Igα, respectively. The pRp261-IgαK198 mutant vector was generated by PCR. PRMT1, 3, 5, and 6 were cloned in the pcDNA3.1 vector containing one flag- and two tandem HA-tags at the N terminus.

siRNA. HEK293 cells were stably transfected with CD8-Igα (this chimeric protein contains the extracellular and the transmembrane region of the mouse CD8α fused with the cytoplasmic tail of mouse Igα). The siRNAs (80 nM final concentration) were complexed with Cellfectin (Invitrogen) in Opti-tum medium for 25 min and were applied to the cells. After 4 h, DMEM (supplied with 10% FCS without phenol red and antibiotics) was added and incubated for 72 h. To target human PRMT1, the siRNA oligonucleotide was purchased from Santa Cruz Biotechnology, Inc. The nontargeting control siRNA was from Thermo Fisher Scientific.

Antibodies and reagents. The following antibodies were used for Western blotting: antiphosphotyrosine (4G10), anti-GST (Bethyl Laboratories, Inc.), anti-HA (Roche), anti-flag (Sigma–Aldrich), antiactin, and anti-Syk (N19; Santa Cruz Biotechnology, Inc.), anti-pY630-Syk (Kulathu et al., 2008), anti-PRMT1, and anti-p543-PKB (Cell Signaling Technology). For immunoprecipitation, the following antibodies were used: anti-flag (Sigma–Aldrich) and anti-HA (12CA5). The anti-methyl-Igα (anti–R<sup>−</sup>–Igα) antibody was generated by immunizing rabbit with mono–methyl-Igα peptide (190–202 aa). Affinity purification of the antisera was performed to produce a methyl-specific antibody (Eurogentec).

W. Sippl (Martin-Luther-Universität Halle-Wittenberg, Halle, Germany) provided the PRMT1 inhibitor (N3C 35605). The inhibitor was obtained from the National Cancer Institute/Developmental Therapeutics Program Open Chemical Repository (available at http://dtp.cancer.gov).

In vitro methylation assays. 2 µg GST and GST Igα recombinant proteins were incubated with 10 µl of immunoprecipitated PRMT enzymes. 0.5 µCi S-adenosyl-L-[methyl-<sup>3</sup>H)methionine (the methyl group donor) was added and the reaction was incubated for 1 h at 30°C. The samples were loaded on a gel and blotted onto a nitrocellulose membrane.

Figure 6. Igα methylation supports B cell development. Igα KO cells (control) infected with IgαWT or IgαK198 were intravenously transferred into RAG-2<sup>−/−</sup>/γ<sup>−/−</sup> mice. 10 d after injection, the resulting B cells were analyzed by flow cytometry. (A) Splenic B cells were shown in the dot plot with anti-CD19 and anti-IgM antibodies. The cells were gated on the GFP<sup>+</sup> population. The percentages of CD19<sup>+</sup>IgM<sup>+</sup> cells are indicated. (B) The histogram shows the amount of BCR (IgM) on the surface of GFP<sup>+</sup> BM cells. (C) The numbers of transferred cells found in the spleen (left) and in the BM (right) are plotted. Error bars indicate means + SEM (each with three mice; *, P < 0.04; **, P < 0.01). The cell transfer was performed two times using three mice per group per experiment. In these two sets of experiments, the cells were separately infected and sorted based on GFP expression.
In vivo methylation assay. 2 × 10⁶ B cells/ml were incubated in RPMI 1640 complete medium (10% heat-inactivated FCS, 100 U/ml penicillin/ streptomycin [Invitrogen], 50 μM 2-mercaptopethanol, and IL-7, without methionine) containing 20 μg/ml chloramphenicol and 100 μg/ml cycloheximide (Sigma–Aldrich) for 30 min. The medium was replaced with RPMI 1640 complete medium containing 10 μCi/ml of L-[methyl–H]methionine (GE Healthcare). The cells were incubated for an additional 3 h in the presence of the methyl group donor and the same protein synthesis inhibitors.

Isolation of primary B cells. B cells were isolated from the spleen of WT BALB/c mice by depletion with an anti-CD43 antibody coupled to magnetic microbeads using an automated magnetic cell sorter (autoMACS; Miltenyi Biotec). The negative fraction obtained by magnetic sorting was stained with CD19-FITC, CD93–allophycocyanin (APC), CD21–PE, and CD23–PE-Cy7 (eBioscience), Translational (CD19*CD93*), follicular (CD19*CD93*CD23*CD21*), and marginal zone (CD19*CD93*CD23*CD21+) B cells were sorted by a FACSARia (BD; Matthias and Rolink, 2005). All B cell populations were 99% pure. Pre-B cells (CD19+CD25−), derived from BM of WT BALB/c mice, were sorted using the following antibodies: CD19–FITC and CD25–PE (eBioscience).

In situ PLA. Unstimulated or stimulated B cells were centrifuged onto microscope slides fixed with 2% PFA for 30 min on ice, permeabilized with 0.5% saponin for 3 min, and stained according to the manufacturer’s instructions with the Duolink kit (Olink Bioscience). The antibody combinations used were rabbit–anti-Igα/mouse–anti–PRMT1 (Eurogentec and Abcam, respectively) or rabbit–anti-Igμ/mouse–anti–Syk (4D10; Eurogentec and Santa Cruz Biotechnology, Inc., respectively). The nuclei were stained with Hoechst. The images of the cells were taken with a confocal microscope (SP2; Leica), and they have been acquired with one z-plane. The image analysis was performed with the freeware BlobFinder (available at http://www.cb.uu.se/~amin/BlobFinder/).

Measurement of Ca²⁺ release. 3 × 10⁶ cells were incubated with 5 μg/ml Indo-1 and 0.5 μg/ml pluronic acid (Invitrogen) in Iscove’s medium supplemented with 1% FCS at 37°C for 45 min. The loaded cells were resuspended in Iscove’s medium containing 1% FCS, and Ca²⁺ release was induced by the addition of 1 μg/ml NIP-conjugated BSA (15 hapten per BSA molecule; Biosearch Technologies) or 10 μg/ml of goat anti-mouse IgM (SouthernBiotech). Ca²⁺ flux was measured with an LSR II (BD).

Cell stimulation and immunoprecipitation. 2 × 10⁶ B cells were resuspended in plain Iscove’s medium and stimulated with 20 ng/ml NIP-BSA at 37°C for the times indicated in the figures. Pellets were lysed on ice for 30 min in lysis buffer containing 20 mM Tris-HCl, pH 7.6, 137 mM NaCl, 10% glycerol, 2 mM EDTA, 500 μM sodium orthovanadate, 1 mM NaF, 0.5% Brij96, and protease inhibitor cocktail (Sigma–Aldrich). Where indicated in the figures, immunoprecipitation with anti-flag antibody was performed. Lysates were separated by SDS-PAGE, and Western blot analysis was made using an enhanced chemiluminescence system (Thermo Fisher Scientific).

Stably transfected HEK293 cells were lysed on ice for 30 min in Ex-250 lysis buffer (20 mM Heps, pH 7.5, 250 mM NaCl, 0.5 mM MgCl₂, 0.5% NP-40). The lysates were centrifuged for 10 min at 1,000 g, and the supernatant was further diluted with Ex-0 (20 mM Heps, pH 7.5, 0.5 mM MgCl₂, 0.5% NP-40) to a final concentration of 150 mM NaCl and centrifuged for 20 min at 20,000 g. Lysates were immunoprecipitated with anti-HA antibody (12CA5) and 15 μl of protein G sepharose (50% slurry). The beads were washed with Ex-150 buffer (20 mM Heps, pH 7.5, 150 mM NaCl, 0.5 mM MgCl₂, 0.5% NP-40) and PBS, and were finally resuspended in 50 μl PBS.

FACS analysis. Cells were resuspended in PBS, 1% FCS, and 0.01% NaN₃, and were incubated on ice with anti–κ-biotin and anti–λ-biotin (Southern-Biotech) followed by streptavidin-Cy5 (Jackson ImmunoResearch Laboratories, Inc.) or with anti-flag–APC (PerkinElmer) and goat anti-mouse IgM–Alexa Fluor 647 (Invitrogen). Dead cells were excluded by staining with 10 μg/ml propidium iodide. FACS analysis was performed with a flow cytometer (FACSCalibur; BD).

Online supplemental material. Fig. S1 shows the specificity of the anti–R-Ilgs antibody. Fig. S2 depicts BCR- and pre-BCR expression in WT or mutant Igα-expressing cells. Fig. S3 shows PRMT1 expression in B cells. Fig. S4 shows the statistical analysis of the in vitro differentiation assay. Online supplemental material is available at http://www.jem.org/cgi/content/full/jem.20091303/DC1.

The authors would like to dedicate this work to the memory of the late Dr. Koshland Jr., whose work on the methylation of chemokatax receptors and signaling in bacteria had an early and important impact on the emerging field of signaling.

We thank Dr. E. Hobeika for generating Igα-deficient pro-B cells; H. Schley, R. Vogt, U. Stauffer, and U. Zeissler for technical assistance; S. Hobitz and A. Wuerch for cell sorting; Dr. P.J. Nielsen for critical reading of the manuscript; and Drs. S. Saccani and D. Van Essen for helpful discussion.

This work was supported by the Swiss National Foundation (fellowship PBEBB–112763), the Human Frontier Science Program career development award, the European Research Council, the Epigenome Network of Excellence (to R. Schneider), the Deutsche Forschungsgemeinschaft (through SFB746), and the Excellence Initiative of the German federal and state governments (EXC294).

The authors have no conflicting financial interests.

Submitted: 15 June 2009
Accepted: 11 February 2010

REFERENCES

Amin, R.H., and M.S. Schlissel. 2008. Foxo1 directly regulates the transcription of recombination-activating genes during B cell development. Nat. Immunol. 9:613–622. doi:10.1038/nii.1162

Bedford, M.T. 2007. Arginine methylation at a glance. J. Cell Sci. 120:613–624. doi:10.1242/jcs.019885

Bedford, M.T., and S.G. Clarke. 2009. Protein arginine methylation in mammals: who, what, and why. Mol. Cell. 33:1–13. doi:10.1016/j.molcel.2008.12.013

Blanchet, F., A. Cardona, F.A. Letimier, M.S. Hershfield, and O. Acuto. 2005. CD28 costimulatory signal induces protein arginine methylation in T cells. J. Exp. Med. 202:371–377. doi:10.1084/jem.20050176

Blanchet, F., B.T. Schurter, and O. Acuto. 2006. Protein arginine methylation in lymphocyte signaling. Curr. Opin. Immunol. 18:321–328. doi:10.1016/j.coi.2006.03.001

Colucci, F., C. Soudais, E. Rosmarak, I. Vanes, V.L. Tybulewicz, and J.P. Di Santo. 2009. Dissecting NK cell development using a novel alymphoid mouse model: investigating the role of the c-abl proto-oncogene in murine NK cell differentiation. J. Immunol. 182:2761–2765.

Flemming, A., T. Brunner, M. Reth, and H. Jumaa. 2003. The adaptor protein SLP-65 acts as a tumor suppressor that limits pre-B cell expansion. Nat. Immunol. 4:38–43. doi:10.1038/ni862

Gary, J.D., and S. Clarke. 1998. RNA and protein interactions modulated by protein arginine methylation. Prog. Nucleic Acid Res. Mol. Biol. 61:65–131. doi:10.1016/S0079-6603(08)60825-9

Gary, D., T. Saunders, S. Camper, and M. Weigert. 1993. Receptor editing: an approach by autoantibody B cells to escape tolerance. J. Exp. Med. 177:999–1008. doi:10.1084/jem.177.4.999

Gazumyan, A., A. Reichlin, and M.C. Nussenzweig. 2006. Igα internalization. J. Cell Sci. 119:65–131. doi:10.1242/jcs.01988

Grucza, R.A., K. Fütterer, A.C. Chan, and G. Waksman. 1999. Protein SLP-65 acts as a tumor suppressor that limits pre-B cell expansion. J. Exp. Med. 182:2761–2765.

Hemsley, J. 2009. The N terminus of the non-T cell activating MHC class II alpha chain inactivates the CD40 signalling pathway in T cells. J. Immunol. 182:2336–2343.

Herzog, S., and H. Jumaa. 2007. The N terminus of the non-T cell activation linker (NTAL) confers inhibitory effects on pre-B cell differentiation. J. Immunol. 178:2336–2343.

Herzog, S., E. Hug, S. Meixlberger, J.H. Paik, R.A. DePinho, M. Reth, and H. Jumaa. 2008. SLP-65 regulates immunoglobulin light chain gene
recombination through the PI(3)K-PKB-Foxo pathway. *Nat. Immunol.* 9:623–631. doi:10.1038/ni.1616

Herzog, S., M. Reth, and H. Jumaa. 2009. Regulation of B-cell proliferation and differentiation by pre-B-cell receptor signalling. *Nat. Rev.* 9:195–205.

Kraus, M., M.B. Alimzhanov, N. Rajewsky, and K. Rajewsky. 2004. Survival of resting mature B lymphocytes depends on BCR signalling via the Igalpha/beta heterodimer. *Cell.* 117:787–800. doi:10.1016/j.cell.2004.05.014

Kulathu, Y., E. Hobeika, G. Turchinovich, and M. Reth. 2008. The kinase Syk as an adaptor controlling sustained calcium signalling and B-cell development. *EMBO J.* 27:1333–1344. doi:10.1038/emboj.2008.62

Lawson, B.R., Y. Manenkova, J. Ahamed, X. Chen, J.P. Zou, R. Baccala, A.N. Theofilopoulos, and C. Yuan. 2007. Inhibition of transmethylation down-regulates CD4 T cell activation and curtails development of autoimmunity in a model system. *J. Immunol.* 178:5366–5374.

Matthias, P., and A.G. Rolink. 2005. Transcriptional networks in developing and mature B cells. *Nat. Rev. Immunol.* 5:497–508.

Meixlsperger, S., F. Köhler, T. Wossning, M. Reppel, M. Müschen, and H. Jumaa. 2007. Conventional light chains inhibit the autonomous signaling capacity of the B cell receptor. *Immunity.* 26:323–333. doi:10.1016/j.immuni.2007.01.012

Mowen, K.A., B.T. Schurter, J.W. Fathman, M. David, and L.H. Glimcher. 2004. Arginine methylation of NIP45 modulates cytokine gene expression in effector T lymphocytes. *Mol. Cell.* 15:559–571. doi:10.1016/j.molcel.2004.06.042

Najbauer, J., B.A. Johnson, A.L. Young, and D.W. Aswad. 1993. Peptides with sequences similar to glycine, arginine-rich motifs in proteins interacting with RNA are efficiently recognized by methyltransferase(s) modifying arginine in numerous proteins. *J. Biol. Chem.* 268:10501–10509.

Nemazee, D.A., and K. Bürki. 1989. Clonal deletion of B lymphocytes in a transgenic mouse bearing anti-MHC class I antibody genes. *Nature.* 337:562–566. doi:10.1038/337562a0

Pelanda, R., E. Hobeika, T. Kurokawa, Y. Zhang, S. Kuppig, and M. Reth. 2002. Cre recombinase-controlled expression of the mb-1 allele. *Genes.* 32:154–157. doi:10.1002/gene.10070

Reth, M. 1989. Antigen receptor tail clue. *Nature.* 338:383–384. doi:10.1038/338383b0

Reth, M., G.J. Hämmerling, and K. Rajewsky. 1978. Analysis of the repertoire of anti-NP antibodies in C57BL/6 mice by cell fusion. *I. Characterization of antibody families in the primary and hyperimmuneresponse. Eur. J. Immunol.* 8:393–400. doi:10.1002/eji.1830080605

Rolink, A., A. Kudo, H. Karasuyama, Y. Kikuchi, and F. Melchers. 1991. Long-term proliferating early B cell lines and clones with the potential to develop to surface Ig-positive, mitogen reactive B cells in vitro and in vivo. *EMBO J.* 10:327–336.

Rolli, V., M. Gallwitz, T. Wossning, A. Flemming, W.W. Schamel, C. Züm, and M. Reth. 2002. Amplification of B cell antigen receptor signaling by a Syk/ITAM positive feedback loop. *Mol. Cell.* 10:1057–1069. doi:10.1016/S1097-2765(02)00739-6

Scharenberg, A.M., L.A. Humphries, and D.J. Rawlings. 2007. Cyclin signalling and cell-fate choice in B cells. *Nat. Rev. Immunol.* 7:778–789.

Spannhoff, A., R. Heinke, I. Bauer, P. Trojer, E. Metzger, R. Gust, R. Schüle, G. Brosch, W. Sippl, and M. Jung. 2007. Target-based approach to inhibitors of histone arginine methyltransferases. *J. Med. Chem.* 50:2319–2325. doi:10.1021/jm061250e

Srinivasan, L., Y. Sasaki, D.P. Calado, B. Zhang, J.H. Paik, R.A. DePinho, J.L. Kutok, J.F. Kearney, K.L. Otipoby, and K. Rajewsky. 2009. PI3 kinase signals BCR-dependent mature B cell survival. *Cell.* 139:573–586. doi:10.1016/j.cell.2009.08.041

Yamagata, K., H. Dutoku, Y. Takahashi, K. Namuki, K. Hnatake, K. Kako, H. Mukai, Y. Kasuya, and A. Fukamizu. 2008. Arginine methylation of FOXO transcription factors inhibits their phosphorylation by Akt. *Mol. Cell.* 32:221–231. doi:10.1016/j.molcel.2008.09.013
Author/s:
Infantino, S; Benz, B; Waldmann, T; Jung, M; Schneider, R; Reth, M

Title:
Arginine methylation of the B cell antigen receptor promotes differentiation.

Date:
2010-04-12

Citation:
Infantino, S., Benz, B., Waldmann, T., Jung, M., Schneider, R. & Reth, M. (2010). Arginine methylation of the B cell antigen receptor promotes differentiation.. J Exp Med, 207 (4), pp.711-719. https://doi.org/10.1084/jem.20091303.

Persistent Link:
http://hdl.handle.net/11343/257212

License:
CC BY-NC-SA