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Journal: Blood

Year: 2008 Feb 1

Volume: 111

Issue: 3

Pages: 1004-12

DOI: 10.1182/blood-2007-09-110874

TACI, unlike BAFF-R, is solely activated by oligomeric BAFF and APRIL to support survival of activated B cells and plasmablasts

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Running title: TACI requires oligomerized ligands
Word count: 4881

Abbreviations:
APRIL: A PRoliferation-Inducing Ligand; BAFF: B cell Activating Factor of the TNF Family; BCMA: B Cell Maturation Antigen; TACI: Transmembrane Activator and CAML-Interactor.

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Abstract

The cytokine BAFF binds to the receptors TACI, BCMA and BAFF-R on B cells, whereas APRIL binds to TACI and BCMA only.

The signaling properties of soluble trimeric BAFF (BAFF 3-mer) were compared to those of higher order BAFF oligomers. All forms of BAFF bound BAFF-R and TACI, and elicited BAFF-R-dependent signals in primary B cells. In contrast, signaling through TACI in mature B cells or plasmablasts was only achieved by higher order BAFF and APRIL oligomers, all of which were also potent activators of a multimerization-dependent reporter signaling pathway. These results indicate that although BAFF-R and TACI can provide B cells with similar signals, only BAFF-R, but not TACI, can respond to soluble BAFF 3-mer, which is the main form of BAFF found in circulation. BAFF 60-mer, an efficient TACI agonist, was also detected in plasma of BAFF transgenic and non-transgenic mice and was greater than 100-fold more active than BAFF 3-mer for the activation of multimerization-dependent signals. TACI supported survival of activated B cells and plasmablasts *in vitro*, providing a rational basis to explain the immunoglobulin deficiency reported in TACI-deficient individuals.

Introduction

B-cell activating factor of the TNF family (BAFF, also known as BLyS) and A Proliferation-Inducing Ligand (APRIL) are two members of the TNF family mainly involved in B cell physiology (reviewed in [1-3]). BAFF is expressed by myeloid cells and by unidentified radiation-resistant cells, possibly stromal cells of secondary lymphoid organs [4-6]. BAFF is either expressed at the cell surface or released into a soluble form through cleavage by an uncharacterized furin [7-9]. Members of the TNF family usually assemble as trimers [10], but soluble BAFF was crystallized both as a trimer and as a virus-like structure resulting from the ordered assembly of twenty trimers through an unusually long loop of BAFF between β-sheets D and E (DE loop) [11,12]. Although the physiological relevance of BAFF 60-mer has not been studied, recent work showed that BAFF 60-mer was also produced by cells expressing BAFF endogenously, and that the 60-mer was moderately more potent than the 3-mer at co-stimulating BCR-induced thymidine uptake in primary B cells [13]. APRIL, a close homologue of BAFF, can also co-stimulate B cells but requires oligomerization in order to do so [14].

BAFF and APRIL share two receptors, namely TACI (transmembrane activator and CAML interactor) and BCMA (B cell maturation antigen). In addition, BAFF binds to a third receptor, BAFF-R, also known as BR3. The role of BAFF in peripheral B cell development is well recognized. B cells are generated in the bone marrow, which they exit at an immature stage. Subsequent maturation takes place in the spleen, where B cells evolve through the transitional T1 and T2 stages to mature follicular B cells or marginal zone B cells. Encounter with antigen leads to B cell activation and differentiation into

memory B cells or antibody secreting plasmocytes, whose survival in the bone marrow requires BAFF and/or APRIL [14,15].

In BAFF-deficient mice, the reduced expression of CD21 and CD23 by B cells was initially interpreted as a blockade at the T1 stage, but it was shown later that subsequent maturation steps also occurred in BAFF-deficient mice, but at reduced frequency [16]. This finding is in line with the broad survival function of BAFF described for both transitional and mature B cells [17,18], and with the fact that BAFF can be functionally replaced by enforced expression of the anti-apoptotic factor Bcl-2 in B cells, further pointing to its prosurvival function [19]. BAFF-R-deficiency recapitulates most of the phenotype of BAFF-deficient mice, but affects T-dependent and T-independent humoral responses less severely [20], suggesting that although BAFF-R transmits important BAFF signals, there are other functional receptors for BAFF *in vivo*.

The role of APRIL in B cell physiology is less well established. One strain of APRIL-deficient mice had lowered IgA serum levels and impaired mucosal IgA responses [21] that were not observed in a second APRIL-deficient strain [22]. Reduced IgA serum levels are also characteristic of TACI-deficient mice, indicating that APRIL might mediate IgA class switch, or survival of switched IgA-secreting cells, through TACI [23]. TACI is generally perceived as a negative regulator of B cells because $TACI^{-/-}$ mice have an enlarged B cell pool that may be linked to autoimmune manifestations [23,24]. TACI-deficient mice are also characterized by reduced antibody responses to T-independent antigens, a feature that is also observed in BAFF-deficient mice [20,23]. Interestingly, about 10% of patients with common variable immunodeficiency (CVID) have mutations in TACI, suggesting a role for TACI in the production of antibodies of various isotypes [25,26].

The third receptor, BCMA, is apparently dispensable for early B cell differentiation stages, but likely plays a role for long-term maintenance of bone marrow plasma cells [15]. To date, the signaling impact of ligand oligomerization has not been investigated in these systems. Here, we studied the ability of BAFF 3-mer and higher order oligomers to signal through BAFF-R and TACI in primary mouse B cells. In contrast to BAFF-R, TACI was unresponsive to BAFF 3-mer, yet provided survival and differentiation signals when triggered by oligomeric forms of BAFF or APRIL. BAFF 60-mer is one form of oligomeric BAFF that can activate TACI and that exists naturally *in vivo*.

Materials and Methods

Mice, cell lines and reagents:

C57/Bl6 mice, 6- to 8-week-old were obtained from Harlan. $TACI^{-/-}$, $BCMA^{-/-}$, $TACI^{-/-}$ x $BCMA^{-/-}$ [20] and BAFF transgenic mice [27] have been described previously. Mice were handled according to institutional and Swiss Federal Office guidelines, as well as under the authorization of the Veterinarian Service of Canton de Vaud.

Jurkat-BCMA:Fas cells (Jurkat-2309 clone 13) were generated as described in supplemental material. Myc-BAFF, BAFF H218A, BAFF A134 and BAFF N242Q, Flag-BAFF, BCMA-Fc, TACI-Fc and BAFF-R-Fc have been described previously [13,28]. Flag-tagged APRIL containing aa 92-233 of human APRIL was purified from supernatants of transiently transfected 293T cells (see supplemental material). The hamster mAb B9C11 anti-mouse BAFF-R was kindly provided by Dr Melissa Starovasnik (Genentech, San Francisco). Commercial reagents were as follow: rat IgM Buffy-2 anti-human BAFF, rat IgG1 5A8 anti-mouse BAFF and rat IgG1 1C9 anti-mouse BAFF (Alexis), anti-Flag M2

mAb and biotinylated M2 mAb (Sigma), carboxy fluorescein diacetate succinimide ester (CFSE) (Molecular Probe), mouse IL-4 and mouse IL-6 (PeproTech).

Cytotoxicity assay:

The cytotoxicity assay using BCMA:Fas Jurkat cells was performed as described for FasL on Jurkat cells [29]. When stated, the assay was performed in the presence of 1.5 μg/ml of cycloheximide to increase susceptibility of the cells to apoptosis. In some instances, BCMA-Fc was added at a final concentration of 2.5 μg/ml to assess the specificity of the assay.

For membrane-bound BAFF, 293T cells were transfected with an uncleavable form of full length mouse BAFF (R125A and R126A) and incubated for 16 h with a fixed number of Jurkat BCMA:Fas target cells and various ratio of effector cells. Cell death was assessed by FACS, based on the FSC/SSC profile that allows discriminating 293T cells from live Jurkat cells from dead Jurkat cells. To monitor BAFF in transfected 293T cells, cells were lysed in 20 mM Tris-HCl pH 7.4, 150 mM NaCl, 1% Triton-X100, Cømplete™ protease inhibitor cocktail (Roche), and BAFF was quantified in the lysate by ELISA (see supplemental material).

Gel permeation chromatography:

293T cells were transiently transfected with a full-length mouse BAFF cDNA and grown for 7 days in carbonate-buffered medium. Cell supernatants or mouse plasma (200 μl) were fractionated by gel filtration on Superdex-200 as previously described [13] and

analyzed by Western blotting using Buffy-2 mAb, or by ELISA (see supplemental material). Fractions were also tested for their ability to kill Jurkat BCMA:Fas cells.

Characterization of ligand - receptor interactions:

Immunoprecipitation of TACI-Fc with Protein A-Sepharose followed by Western blot analysis, and detection of ligand-receptor interactions by ELISA were performed according to standard techniques (see supplemental material).

Splenocyte survival, co-stimulation and MHC class II upregulation assays:

A detailed protocol is provided in the supplemental material. Briefly, B220-purified B cells were grown for 66 h in the presence of ligands, anti-Flag and anti-BAFF-R antibodies as required. Viable cells were identified based on the FSC/SSC profile. B cell proliferation in response to an anti-mouse μ chain F(ab')2 antibody was monitored by thymidine incorporation. In some experiments, B cells were stained with CFSE prior to cultivation. MHC class II upregulation was monitored by FACS analysis.

Ig production assay:

Purified splenic B cells (10^6/well in 1ml of complete RPMI, 24-well plates) were grown for 6 days in the presence of the different ligands at 100 ng/ml. When specified, IgA^+ B cells were depleted by incubation with biotinylated goat anti-mouse IgA (1:500; Caltag) for 10 minutes at 4°C followed by streptavidin-conjugated magnetic beads (Miltenyi Biotech). IgA and IgM titers in culture supernatants were quantified by ELISA (see supplemental material).

Plasmablasts survival assays:

10- to 12-week-old mice were injected s.c. into hind footpads with 10^7-10^8 MMTV particles in infected milk [30]. MMTV (SW) encodes a Vβ6-specific superantigen. Synchronized plasmablasts were isolated from the draining popliteal lymph nodes 6 days after infection, and purified with PE-conjugated anti-mouse CD138 (Becton Dickinson) and anti-PE magnetic beads (Miltenyi Biotech). Purified plasmablasts (10^5/well in 200 µl of complete RPMI) were incubated for 44 hours with different ligands at 500 ng/ml. Number of viable plasmablasts were analyzed by IgG2a/c ELISPOT (see supplemental material).

Survival of $CD138^+$, tetanus toxoid-specific splenic plasmablasts, obtained at the peak of a booster response, was measured in the presence or absence of various BAFF and APRIL proteins, essentially as described [31,32]. See also supplemental material.

Results

Natural and engineered BAFF oligomers are more potent than BAFF 3-mer at delivering multimerization-dependent signals.

Some TNF family ligands are not biologically active as soluble trimers, but gain activity when oligomerized by fusion with the Fc portion of an immunoglobulin, or by addition of cross-linking antibodies, thereby mimicking the membrane-bound form of the ligand [29,33]. It is not known whether the activity of BAFF is conditioned by its level of oligomerization, such as those found in BAFF 3-mer and BAFF 60-mer [13,34]. In order to monitor the activity of BAFF 3-mer and oligomers, a surrogate cell death assay was

developed, in which the oligomerization-dependent apoptotic Fas pathway can be initiated by BAFF. For this purpose, a fusion protein consisting of the extracellular domain of BCMA fused to the transmembrane and intracellular domains of Fas was expressed in Jurkat T cells. Clones that underwent apoptosis in response to BAFF were selected. Ligands tested included BAFF 3-mers (myc-BAFF, Flag-BAFF and BAFF with mutation H218A preventing 60-mer formation) and various BAFF oligomers (*i.e.* containing two or more BAFF 3-mers within the same complex) such as Fc-BAFF, Flag-BAFF plus anti-Flag, or BAFF 60-mers (BAFF starting at the natural processing site A134, with or without mutation N242Q that prevents N-glycosylation. See suppl. figure 1). Stimulation of Jurkat BCMA:Fas cells revealed that all BAFF oligomers were two to three orders of magnitude more potent than BAFF 3-mers at inducing cell-death through the surrogate, multimerization-dependent Fas signaling pathway (Figure 1A).

In order to determine whether membrane-bound BAFF can trigger a multimerization-dependent pathway, a non-cleavable form of full length BAFF with mutations R125A and R126A in the furin-processing site was generated (Suppl. figure 2). Cells expressing non-cleavable membrane-bound BAFF were at least 50-fold more active than soluble BAFF 3-mer on BCMA:Fas Jurkat cells, indicating that membrane-bound BAFF can indeed be assimilated to an oligomeric ligand (Figure 1B). Membrane-bound BAFF was apparently less active that soluble BAFF 60-mer in this assay (Figure 1B), possibly because only a fraction of membrane-bound BAFF is expressed at the cell surface.

In order to determine whether initiation of productive signaling through unmodified BCMA was also sensitive to BAFF oligomerization, BCMA-transfected 293T cells were exposed to BAFF 3-mer or BAFF 60-mer, and monitored for the activation of a NF-κB

reporter system. In this assay, BAFF 60-mer readily induced a robust, BCMA-dependent NF-κB signal, whereas BAFF 3-mer was roughly 1000-fold less active (Suppl. figure 3).

The difference between BAFF 3-mer and BAFF 60-mer observed in both assays could not be accounted for by differential binding to the receptor, as both proteins bound TACI-Fc in immunoprecipitation experiments (Figure 1C) and similarly bound BCMA, TACI and BAFF-R in an ELISA assay (Figure 1D). Only BAFF N242Q displayed a comparatively reduced affinity (Figure 1D), that probably explains why it was somewhat less active than BAFF A134 (Figure 1A).

These results indicate that BAFF oligomers, including membrane-bound BAFF and BAFF 60-mer, are activators of multimerization-dependent signaling pathways.

The anti-mouse BAFF-R antibody B9C11 antagonizes BAFF-BAFF-R signals.

Receptor-deficient mice were used to study the impact of ligand oligomerization on BAFF-R and TACI signaling in primary B cells. However, instead of using BAFF-$R^{-/-}$ B cells that are not only scarce but also immature, BAFF-R-expressing B cells were treated with a blocking anti-BAFF-R antibody (B9C11). Despite a weak agonist activity, B9C11 completely abrogated the pro-survival effects of Myc-BAFF (3-mer), BAFF H218A (3-mer) and BAFF N242Q (60-mer), and also antagonized the pro-survival effects of BAFF A134 (60-mer) at concentrations below 20 ng/ml (Figure 2M-P). Thus, B9C11 prevents BAFF signaling through BAFF-R, and can therefore be used to discriminate BAFF signals delivered through BAFF-R from those given through TACI and/or BCMA.

BAFF 3-mer, BAFF oligomers and APRIL co-stimulate B cells through distinct sets of receptors that respond differentially to ligand oligomerization.

The ability of BAFF 3-mers and oligomers to co-stimulate thymidine incorporation in BCR-stimulated primary B cells was tested *in vitro*. For this purpose, ligands were titrated on purified B splenocytes of wild type, $BCMA^{-/-}$, $TACI^{-/-}$ and $BCMA^{-/-}$ x $TACI^{-/-}$ mice, in the presence of stimulating anti-IgM antibodies and with or without addition of the B9C11 anti-BAFF-R antibody at a blocking concentration. Previous work demonstrated that anti-IgM stimulation upregulates TACI in these BAFF-R positive cells [35]. Because APRIL binds to TACI and BCMA, but not to BAFF-R, recombinant Flag-tagged APRIL was also tested, in the presence or absence of cross-linking anti-Flag antibody [14]. We selected human APRIL because it does not bind at all to murine BAFF-R, in contrast to mouse APRIL [36].

Thymidine incorporation in BCR-stimulated wild type B cells was co-stimulated in a dose-dependent manner by BAFF 3-mer, BAFF 60-mer and cross-linked APRIL (Figure 2A, B, Q). Although CFSE-labelled cells underwent division in response to anti-BCR stimulation, co-stimulation with BAFF or cross-linked APRIL increased the number of viable cells without affecting the division pattern (Suppl. figure 4). BAFF also enhanced B cell survival in the absence of B cell receptor stimulation (Suppl. Figure 4). These results suggest that the increased thymidine incorporation mediated by BAFF and APRIL co-stimulation is due mainly, if not entirely, to increased B cell survival.

APRIL-mediated effects were entirely TACI-dependent and insensitive to the presence of the B9C11 anti-BAFF-R antibody (Figure 2S, U, V). In contrast, the survival effect of BAFF 3-mer was abrogated in the presence of B9C11, irrespective of the presence or

absence of TACI and BCMA (Figure 2M, O). Thus, the same biological outcome, B cell survival, was mediated through BAFF-R in response to BAFF 3-mer, and through TACI in response to cross-linked APRIL.

The survival effects of BAFF 60-mers were only reduced by the blocking anti-BAFF-R antibody or by TACI deficiency in isolation, but was abrogated by the combination of both, demonstrating that BAFF 60-mer activated both BAFF-R and TACI (Figure 2A, G K, M). Interestingly, TACI signals were only induced by oligomeric ligands, *i.e.* BAFF 60-mer or cross-linked APRIL, but not by Flag-tagged APRIL or two different BAFF 3-mers. In contrast, BAFF-R signals were triggered by both BAFF 3-mer and BAFF 60-mer.

In addition to BAFF 60-mer and cross-linked APRIL, TACI signalling was also efficiently triggered by Fc-BAFF and cross-linked Flag-BAFF, but not by Flag-BAFF alone, indicating that TACI responds to oligomeric, but not trimeric ligands (Suppl. figure 5). Moreover, signalling of BAFF N242Q (60-mer) through TACI could be inhibited in a dose-dependent manner by an excess of BAFF H218A (3-mer) (Suppl. Figure 6).

Taken together, these results indicate that co-stimulation of BCR-stimulated B cells results from increased cell survival rather than increased cell proliferation, and that different ligands functionally engage different sets of receptors: BAFF 3-mer signals through BAFF-R only, cross-linked APRIL through TACI only, and BAFF 60-mer through both BAFF-R and TACI, the latter receptor responding to oligomeric ligands only. BCMA was not involved in B cell co-stimulation.

TACI-mediated, but not BAFF-R-mediated MHC class II upregulation requires oligomeric ligands.

Murine B cells treated with IL-4 and IL-6 upregulate MHC class II molecules and can present antigens in response to APRIL [37]. MHC class II was upregulated in B cells not only in response to cross-linked APRIL, but also in response to BAFF 3-mer and BAFF 60-mer, but not Flag-APRIL alone (Figure 3). The effect of APRIL was TACI-dependent, whereas that of BAFF 3-mer and BAFF 60-mer was also seen in B cells expressing BAFF-R only (Figure 3). Blocking of BAFF-R with B9C11 completely abrogated the activity of Myc-BAFF (3-mer) and Flag-BAFF (3-mer), but only reduced that of cross-linked BAFF, Fc-BAFF and BAFF 60-mer, indicating that BAFF oligomers can also signal MHC class II upregulation through TACI (Suppl. figure 7). Thus, as shown above for B cell co-stimulation, ligand-mediated upregulation of MHC class II in B cells can be mediated by BAFF-R and TACI, the latter receptor responding to oligomeric ligands. BCMA was not required for MHC class II upregulation.

Increased immunoglobulin production by B splenocytes and plasmablast survival require TACI and oligomerized ligands.

BAFF and APRIL enhance immunoglobulin production in *in vitro* cultures of purified B splenocytes [21]. IgM production in supernatants of B splenocytes cultured for six days was increased 3- and 6-fold in response to cross-linked APRIL and BAFF 60-mer, respectively, an effect that was mainly mediated by TACI (Figure 4A). In contrast, BAFF 3-mer only induced a modest, BAFF-R-dependent response. Although IgA secretion paralleled that of IgM in this assay, this was the result of increased survival of pre-

existing IgA-positive cells rather than isotype switch (data not shown). We conclude that increased IgM and IgA production in this assay was predominantly mediated by TACI in response to oligomerized ligands, with a possible marginal contribution of BAFF-R.

Increased immunoglobulin production can result from either enhanced Ig secretion and/or from a higher number of Ig-secreting cells. In order to specifically address the survival effect of BAFF and APRIL on antibody secreting cells, mice were infected with mouse mammary tumor virus (MMTV) and synchronized plasmablasts were isolated from the draining lymph node six days post-infection [30]. Alternatively, mice were immunized with tetanus toxoid, and plasmablasts were isolated from spleens at the peak of the booster response. Purified plasmablasts were cultured for two days *in vitro*, in the presence or absence of BAFF or APRIL, and the number of viable, antibody secreting cells was quantified by ELISPOT. Under these conditions, numbers of antibody secreting cells were increased 6- to 10-fold in response to BAFF 60-mer or cross-linked APRIL (Figure 4B and C). This effect was impaired in TACI-deficient cells and, to a lesser extent, in BCMA-deficient cells, and was completely abrogated in cells deficient for both TACI and BCMA, indicating that TACI and BCMA, but not BAFF-R, contribute to plasmablast survival. BAFF 3-mer and Flag-APRIL displayed weaker activity than their oligomerized counterparts on responsive B cells, in line with the idea that TACI, and possibly BCMA, require oligomerized ligands. In summary, we conclude that plasmablast survival is enhanced by oligomeric BAFF and APRIL in a TACI- and possibly BCMA-dependent manner.

Formation of 60-mers is a property of both human and mouse BAFF.

If oligomerization of BAFF in the form of a 60-mer were a physiologically relevant feature, as suggested by its specific ability to trigger TACI-dependent responses, it would be expected to be conserved across species. The extended DE loop of BAFF, also known as the "flap" region [12], is not found in other TNF family members but its length is precisely conserved in BAFF of fishes, batrachians, birds and mammals (Figure 5A). Moreover, all residues involved in trimer-trimer interaction, including the histidine residue responsible for pH-dependent assembly of the 60-mer [12,13], are conserved in human, mouse, opossum (marsupial), platypus (monotreme), chicken and 10 further bird and mammalian BAFFs (Figure 5A and data not shown).

It has been previously demonstrated that addition of a short N-terminal Myc tag to soluble BAFF prevents 60-mer formation [13]. Because murine BAFF contains an additional exon encoding 31 amino acid residues close to the mature N-terminus of soluble BAFF [9] (Suppl. figure 1), it is questionable whether mouse BAFF can form 60-mer at all. However, supernatants of 293T cells transfected with full length mouse BAFF contained, in addition to BAFF 3-mer, a fair proportion of a high molecular weight (> 600 kDa) form of processed mouse BAFF, suggesting that it was able to form 60-mers. This conclusion was reinforced by the observation that murine BAFF 60-mer was acid-sensitive and, therefore, no longer detected when analyzed at pH 5 (Figure 5B). We conclude that the formation of a 60-mer is an evolutionarily conserved property of BAFF.

Circulating BAFF 60-mer in BAFF transgenic mice and TACI$^{-/-}$ mice is a major provider of oligomerization-dependent signals.

Although BAFF 60-mer has been previously found in supernatants of human U937 cells [13], it has never been described in *ex vivo* samples. For the purpose of detecting BAFF 60-mer *in vivo*, plasma of BAFF transgenic mice that express full length mouse BAFF under the α1-anti-trypsin promoter [27] was size-fractionated by gel permeation chromatography, and analyzed for its BAFF content by ELISA and for its oligomerization-dependent activity with Jurkat BCMA:Fas cells. Although the majority of BAFF eluted with a size of about 60 kDa (BAFF 3-mer), about 4% of the BAFF protein eluted at a size of about 1000 kDa, compatible with that of BAFF 60-mer, and accounted for two thirds of the total oligomerization-dependent activity (Figure 6A). The activity of this peak was totally abrogated by a soluble decoy receptor and displayed acid sensitivity, further suggesting that it was due to BAFF 60-mer (Figure 6A and data not shown). In line with these results, BAFF 3-mer isolated from plasma of BAFF transgenic mice induced a robust, B9C11-inhibitable survival response in wild type B cells, whereas the more diluted BAFF 60-mer also induced a specific response, but of lower intensity (data not shown).

BAFF 60-mer was then sought in mice that are not transgenic for BAFF. As the Fas pathway used in the bioassay is inhibited by short-lived proteins such as FLIP, its sensitivity can be increased by inhibitors of protein synthesis [38]. Indeed, cycloheximide increased the detection limit of the assay about 10-fold (Suppl. figure 8), but this remained insufficient to detect the activity of a putative BAFF 60-mer in the plasma of wild type mice (Figure 6B). However, under these conditions, BAFF 60-mer was readily detected in the plasma of TACI$^{-/-}$ mice that display about 10-fold elevated circulating BAFF levels compared to wild type mice (Figure 6C).

An additional activity peak of intermediate size and of higher specific activity than BAFF 3-mer was detected in both BAFF transgenic and TACI$^{-/-}$ mice, but was not further characterized (Figure 6A and C).

We conclude from these experiments that several forms of soluble BAFF are found in the plasma of BAFF transgenic and non-transgenic mice, including a low-abundance but highly active BAFF 60-mer.

Discussion

One of most striking finding of this study is the differential ability of BAFF-R and TACI to signal in response to their common ligand BAFF. Although both receptors bind BAFF with high affinity (reviewed in [1]), BAFF-R responded to both BAFF trimers and higher order BAFF oligomers, whereas TACI showed a strict specificity for the latter. This differential signaling behavior was consistently observed in several assays involving B cells at various stages of differentiation, even if the final outcome of the signaling pathways, such as cell survival of upregulation of surface markers, was the same for both receptors.

What are the physiological forms of BAFF that can signal through TACI? An obvious candidate is the membrane-bound form of BAFF that has been identified on myeloid cells [7,8]. Thus, productive signaling through TACI may require cell-cell contacts, ensuring that the signal is delivered at specific sites, and not in a systemic manner. BAFF-R, in contrast, may also respond to soluble BAFF 3-mer which represent the vast majority of systemic BAFF. This situation is reminiscent of TNF-R2 that responds to membrane-bound TNF and TNF-R1 that responds to both membrane-bound and trimeric soluble

TNF [39]. Another candidate activator of TACI signals is BAFF 60-mer, an oligomeric form of BAFF known from crystallographic studies [12,34,40], but for which little or no information exist regarding the function and occurrence *in vivo*. Our study brings about important new elements pointing to possible physiological implications of BAFF 60-mer. First, BAFF 60-mer formation is evolutionarily conserved. Second, an active form of BAFF 60-mer is found in plasma of BAFF transgenic mice, but also in plasma of mice such as $TACI^{-/-}$ with an un-manipulated BAFF gene. Third, BAFF 60-mer and BAFF 3-mer activate different sets of receptors and can therefore be considered as distinct ligands. The originality of BAFF when compared to membrane-bound and soluble TNF is its unique mode of oligomerization as a virus-like particle, its pH-sensitive nature, and the ability to mimic a membrane-bound form of the ligand in a soluble form.

How is it possible to explain that TACI and BAFF-R have different requirements for ligand oligomerization? This may reflect receptor-specific mechanisms of intracellular signaling. TACI binds TNF receptor associated factors (TRAFs) on its intracellular domain (reviewed in [1]). TRAFs are trimeric intermediates in the signaling pathway of numerous TNF receptor family members [41]. By bringing together three receptors, a trimeric ligand may allow recruitment to the complex of just one intracellular TRAF, which may not be enough to induce signaling, as oligomerization of trimeric TRAF-2 and TRAF-6 is required to activate downstream signaling events [42]. BAFF-R only interacts with TRAF-3, whose mode of action and multimerization requirements may be distinct, making BAFF-R-mediated signals less dependent on ligand oligomerization.

Beside promoting survival, BAFF and APRIL also induced upregulation of activation markers such as MHC class II, in line with the enhanced MHC class II expression found in B cells of BAFF transgenic mice at various maturation stages [27]. Although BCMA was reported to induce MHC class II upregulation in IL4- and IL6-stimulated A20 cells [37], our results demonstrate that MHC class II expression in primary B splenocytes can also be stimulated by BAFF-R and TACI signals, and that stimulation with IL4 and IL6 was not essential for this outcome.

It is well documented that BAFF-R induces B cell survival, and BCMA is strongly suspected to promote survival of long-lived plasma cells [15,43]. However, in contrast to BAFF-R and BCMA, TACI is generally described as a negative regulator of B cell survival because TACI-deficient mice have an enlarged B cell pool [23,24], and because an engineered cell line expressing an EDA receptor:TACI chimera could be killed with EDA [24]. In addition, agonist anti-TACI antibodies inhibited proliferation of a B cell line [24], and anti-TACI antibodies prevented Ig secretion in BAFF-R- or CD40-stimulated B cells [24,44]. How can these results be reconciled with our observation that TACI only mediated "positive" events such as survival of primary B cells *in vitro* when engaged by BAFF and/or APRIL? TACI signals triggered with anti-TACI antibodies or with natural ligands may be different, for example because of a differential impact on TACI - proteoglycan interactions, which appear to modulate TACI signals [45,46]. Also, it has not been demonstrated *in vivo* that TACI directly transmits negative signals within B cells: B cell hyperplasia in $TACI^{-/-}$ mice may also result from the loss of a BAFF/APRIL inhibitor such as a soluble, decoy form of TACI. TACI can indeed be processed at Arg^{122}, Arg^{110}

and Lys[108], and each of these cleavage events is predicted to release functional forms of soluble human and mouse TACI [28]. Thus, loss of TACI could remove both a survival signal for TACI expressing cells, and an inhibitor of soluble BAFF, leading to the observed raise of BAFF concentration in TACI$^{-/-}$ mice. As a result, naïve B cells (expressing BAFF-R) would survive better or in greater number due to increased BAFF availability, leading to the observed B cell hyperplasia, whereas plasmablasts and short-lived Ig-secreting cells that preferentially upregulate TACI and play a key role in T-independent humoral responses [3,47] would be specifically penalized by loss of TACI.

Interestingly, T-independent responses are inefficient in TACI$^{-/-}$ mice [23] and BAFF$^{-/-}$ mice [20], but not BAFF-R$^{-/-}$ mice [20], suggesting that they rely on a BAFF/TACI axis that, according to our findings, would require an oligomerized form of BAFF (60-mer or membrane-bound). Loss of TACI also leads to decreased IgA levels [23]. In this respect, we can speculate that the much elevated IgA levels observed in BAFF transgenic mice [27] may be due, at least in part, to BAFF 60-mer acting on TACI. A pro-survival role of TACI is also in line with its up-regulation in several multiple myeloma cell lines [48].

Decreased plasmablast survival could contribute to decreased immunoglobulin levels in CVID patients with TACI mutations. Until now, impaired Ig switch has received great attention to explain the link between TACI-deficiency and CVID [21,25,26]. Nevertheless, IgM levels are often reduced in these patients, indicating that defective Ig switch may not be the sole cause of CVID, in line with an implication of TACI in plasmablast survival.

Inadequate immune responses can lead to autoimmunity, and BAFF overproduction is consistently found in autoimmune diseases such as rheumatoid arthritis, systemic lupus erythematosus (SLE) or Sjögren syndrome [2]. As both short-lived and long-lived Ig-secreting cells are involved in the pathology of SLE, signaling through both TACI and BCMA might contribute to the disease [49]. We have shown that TACI respond to oligomerized ligands, and it will be of interest to determine whether BAFF 60-mer may be produced in excess in these pathologies, and whether the specific targeting of BAFF 60-mer may represent an alternative treatment for these autoimmune disorders.

Acknowledgments

We are grateful to Chantal Tougne (University of Geneva) for expert technical assistance, to Susan Kalled (BiogenIdec, Boston) for her help in providing reagents, to Fang Qian (BiogenIdec) for sharing preliminary results, and to Melissa Starovasnik (Genentech, San Francisco) for providing the B9C11 antibody. This work was supported by grants from the Swiss National Science Foundation, the NCCR Molecular Oncology, and the CTI program (to PS and JT).

Authorship

C.B. performed research, analyzed data and wrote the paper, T.G.C. designed research and contributed vital reagents, A.T., K.I., L.W., A.M., S.C. performed research, M.D., M.L.S., E.B., C.A.S., H.A.O., H.L., F.M. contributed vital reagents and/or techniques, J.T. designed research, P.S. designed research, analyzed data and wrote the paper.

Conflict-of-interest disclosure: T.G. Cachero is a stockholder of BiogenIdec. Other authors declare no competing financial interests.

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Figure legends

Figure 1: **BAFF 3-mer and 60-mer bind BCMA and TACI, but only BAFF 60-mer, BAFF oligomers and membrane-bound BAFF activate a reporter signaling pathway dependent on ligand oligomerization**.

(A) Jurkat T cells expressing a BCMA:Fas chimerical receptor were exposed for 16 h to various concentrations of BAFF 3-mer or 60-mer. Cells were also exposed to Flag-BAFF (3-mer) alone or in the presence of a cross-linking anti-Flag antibody, or to Fc-BAFF (6-mer). Cell viability was measured with the PMS/MTS assay. (B) Jurkat BCMA:Fas cells were incubated with varying ratio of 293T cells transfected with full-length BAFF R125A R126A (293T-BAFF uncleav.) or with empty plasmid (293T mock). Myc-BAFF (3-mer) and BAFF A134 (60-mer) were used instead of cells to calibrate the assay. BAFF present in transfected 293T cells was quantified by ELISA. The highest concentration used (40 ng/ml) corresponds to an effector to target ratio of 1:1. Maximal cell death obtained with this assay was about 50%. (C) BAFF 3-mer and BAFF 60-mer were immunoprecipitated with TACI-Fc. Inputs and immunoprecipitates (IP) were analyzed by Western blotting using an anti-BAFF antibody (Buffy-2). The same blot was re-probed with an anti-Fc antibody (lower panel). The higher band of BAFF carries an N-linked oligosaccharide on asparagine 242, a site that is not used in mammalian cells [9]. Note that recombinant TACI-Fc is partially processed at Lys^{108} and Arg^{110} [28]. (D) Recombinant BCMA-Fc, TACI-Fc

and BAFF-R-Fc were immobilized on ELISA plates and exposed to a fixed concentration of Flag-BAFF, whose binding was visualized with anti-Flag secondary reagents. BAFF 3-mer and BAFF 60-mer were added at the indicated concentrations in order to compete with Flag-BAFF binding and therefore reduce the ELISA signal.

Figure 2: **Co-stimulation of thymidine incorporation in BCR-stimulated B cells by BAFF and APRIL is mediated by both BAFF-R and TACI. TACI responds to oligomerized ligands only.**

Purified B splenocytes of various genotypes were cultured under BCR-stimulating conditions, with or without anti-BAFF-R B9C11, and with the indicated concentrations of BAFF and APRIL. After 48 h, cells were pulsed for 16 h with [^{3}H]-thymidine, harvested and counted. Points represent means ± SD of triplicate cultures. Note that B9C11 abolishes BAFF-mediated effects through BAFF-R. At the concentration used, B9C11 totally blocked BAFF A134 at concentrations up to 10 ng/ml, but only partially at higher concentrations.

Figure 3: **BAFF-R- and TACI-dependent upregulation of MHC class II in B cells.**

(A) Purified wild type and TACI$^{-/-}$ B splenocytes were stimulated plus or minus cross-linked APRIL in the presence of IL-4 and IL-6, and surface expression of MHC class II was monitored by FACS. (B) Experiment was performed as in (A) with B cells of the indicated genotype, and with BAFF and APRIL at the indicated concentrations. MFI: mean fluorescence intensity.

Figure 4: **Enhanced IgM secretion by splenocytes and plasmablast survival require TACI and oligomerized TACI ligands.**

(A) Purified B splenocytes were cultured for 6 days in the presence of 100 ng/ml of the indicated ligands, after which time IgM titers were measured in culture supernatants. The figure shows the fold increase relative to medium only for the same genotype (titers were comparable for the different genotypes). Results are means ± SD of triplicate cultures. (B) MMTV-induced plasmablasts of the indicated genotypes were purified and cultured for two days in the presence of 500 ng/ml of the indicated ligands or 10 ng/ml of IL-6, after which time IgG2a/c-secreting cells were enumerated by ELISPOT. Data are expressed as fold increase compared to wild type B cells in medium only, and represent means ± SD of triplicate (APRIL) or quadruplicate (medium and BAFF) cultures, representative of two experiments with similar results. (C) Tetanus toxoid-specific plasmablasts were purified from spleen at the peak of the booster response, and cultured for two days in the presence of 500 ng/l of the indicated ligands or 10 ng/ml of IL-6. Tetanus toxoid-specific plasmablasts were enumerated by ELISPOT, and the percentage of survival determined relative to values obtained at day 0. Values are mean ± SD of two independent cell preparations (or three preparations for wild type) cultured in triplicates. $p<0.05$: *. $p<0.01$: **.

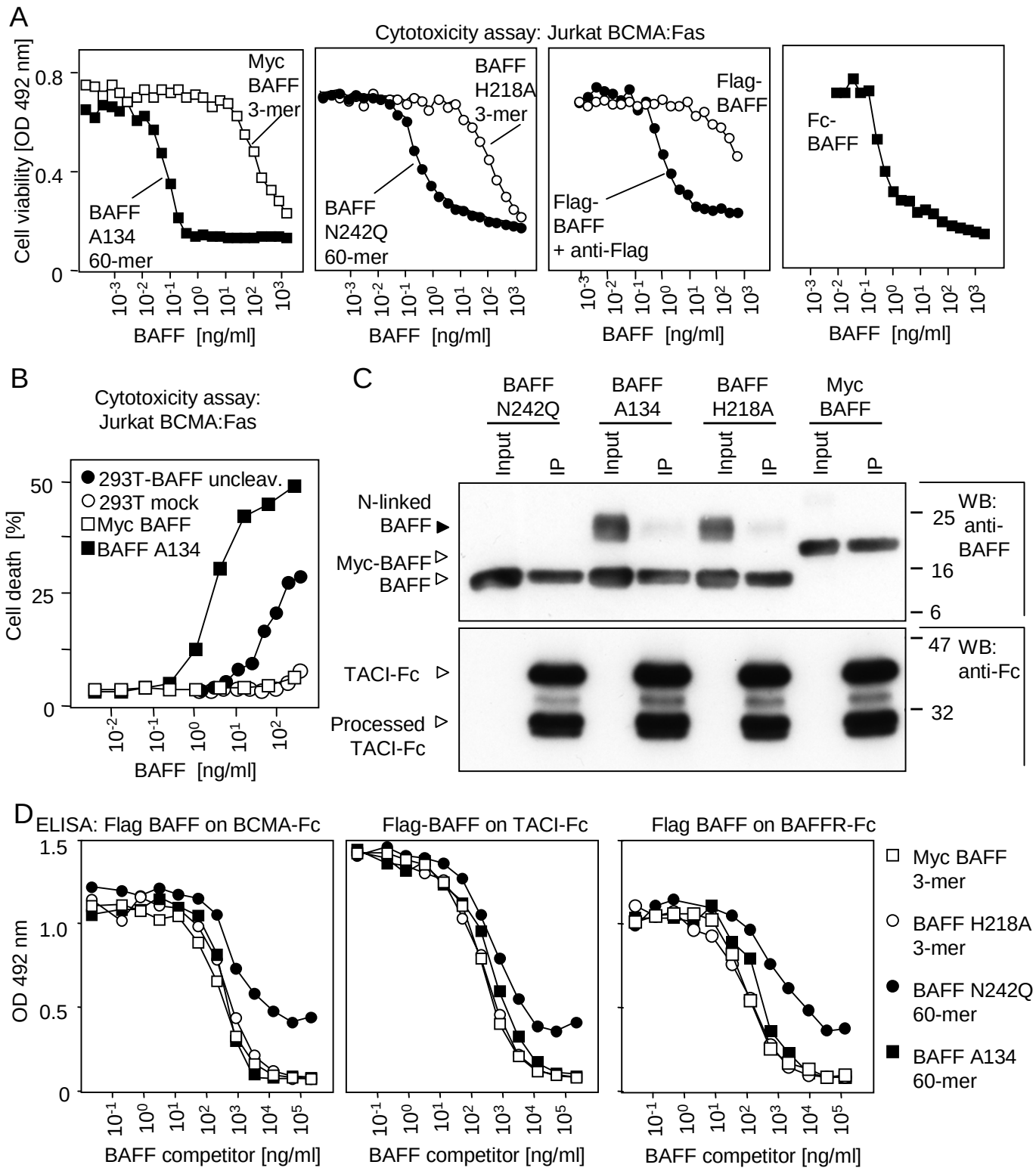
Figure 5: **BAFF 60-mer is conserved across species**.

(A) Alignment of BAFF from various species, and of human TNF family members, in the region of the DE loop. Opossum: *Monodelphis domestica* (GenBank:XP_001375808) . Platypus: *Ornithorynchus anatinus* (GenBank:XP_001514753). Chicken: *Gallus gallus*

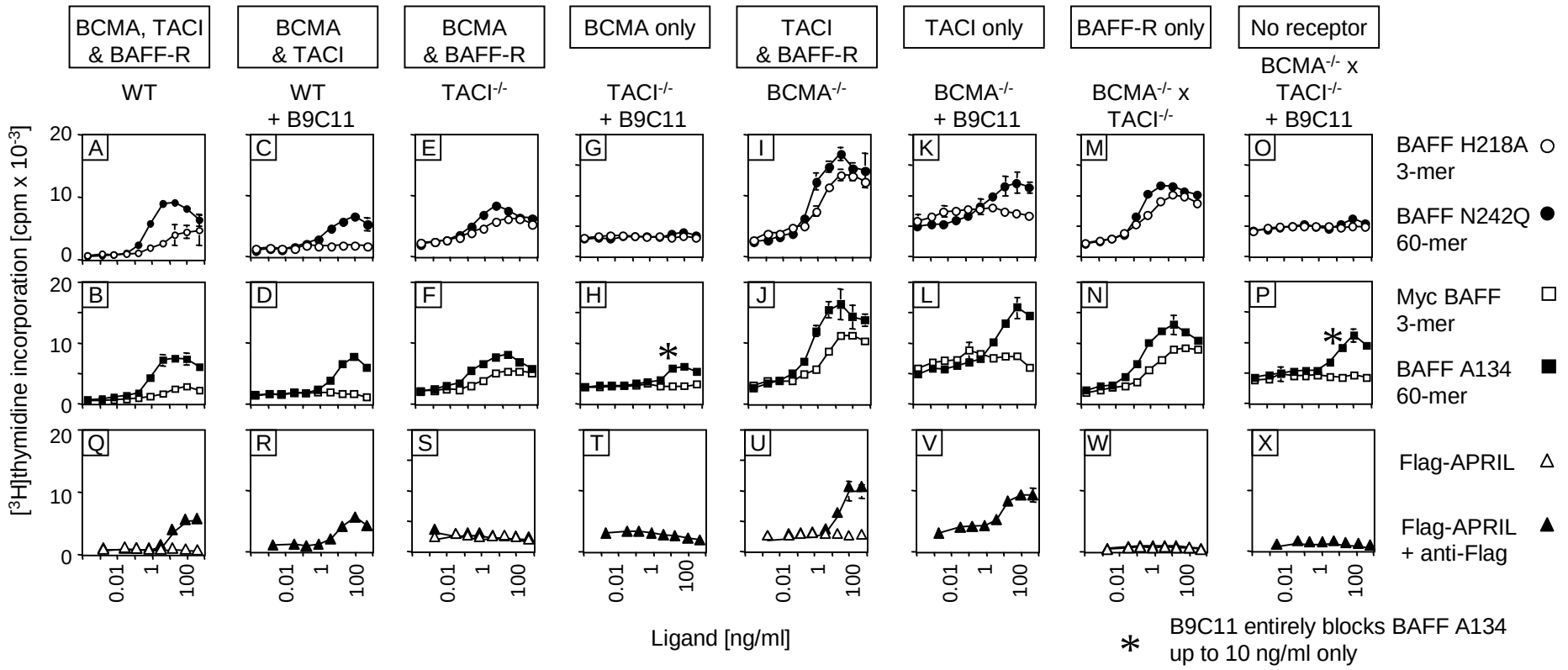
(GenBank:NM_204327). Frog: *Xenopus tropicalis* (EMBL:42:1929088:1912327). Fish: *Danio rerio* **(**GenBank: XM_684671). (B) Gel permeation chromatography analyses of naturally processed mouse BAFF in supernatants of 293T cells transfected with full-length mouse BAFF. Elutions were performed at pH 7.4 or pH 5, and the elution positions of molecular weight standards (in kDa) are indicated at the top of the figure. Fractions were analyzed by western blotting using a cross-reactive anti-human BAFF antibody (Buffy-2).

Figure 6: **Differentially active forms of trimeric and oligomeric BAFF in mouse plasma.**

Plasma from BAFF transgenic, wild type and TACI$^{-/-}$ mice were fractionated by gel permeation chromatography. Mouse BAFF was quantified in the fractions by ELISA (black squares) and expressed with different scales for each genotype. The oligomerization-dependent activity of BAFF in 25 µl, 5 µl and 2.5 µl of wild type, BAFF transgenic and TACI$^{-/-}$ fractions, respectively, was detected with reporter Jurkat BCMA:Fas cells that die in response to oligomerized BAFF (open circles). For wild type and TACI$^{-/-}$ fractions, the assay was performed in the presence of cycloheximide (CHX) that enhances the sensitivity of the assay. Where indicated, BCMA-Fc was added to demonstrate the killing specificity (black circles).



Bossen Figure 1



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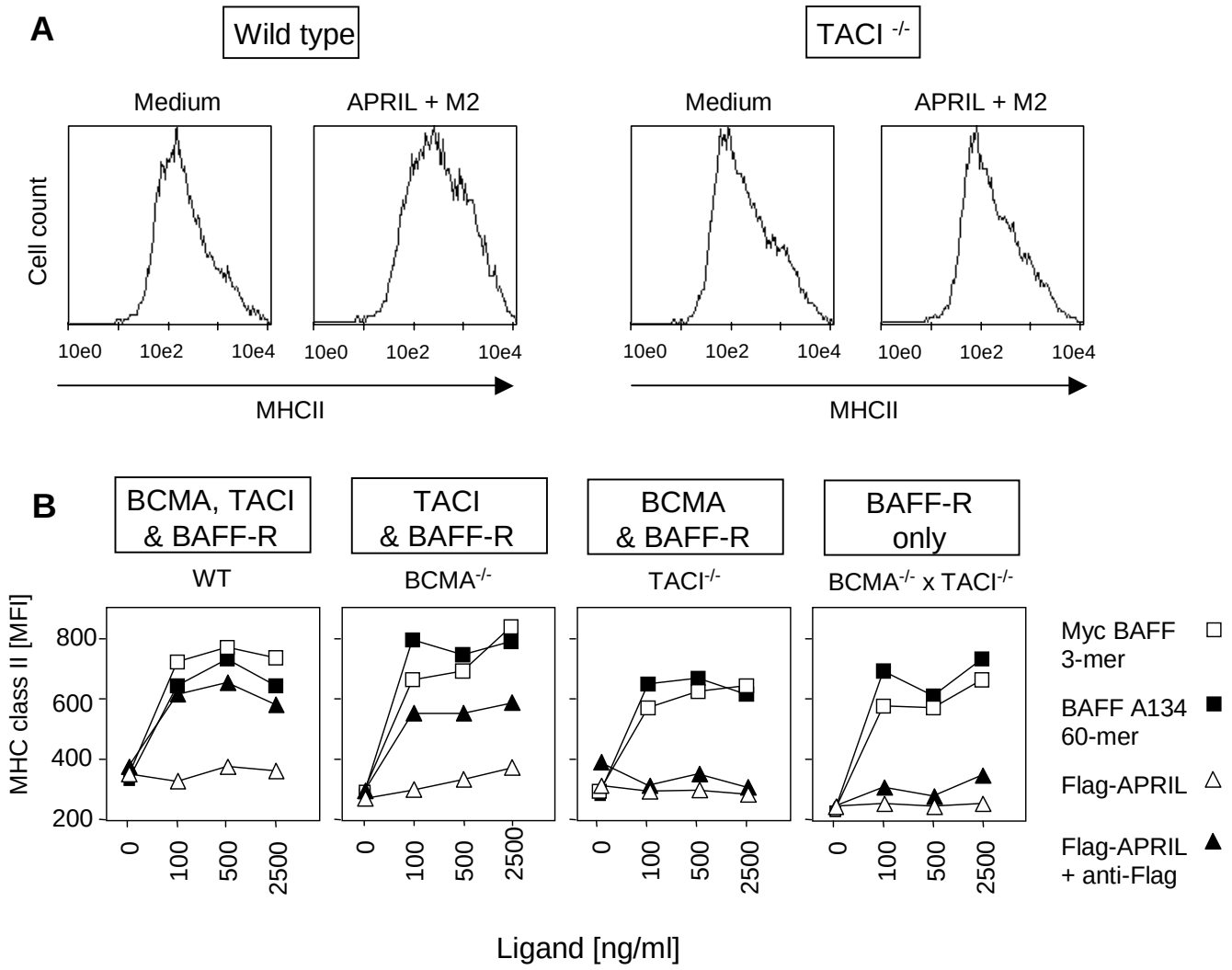

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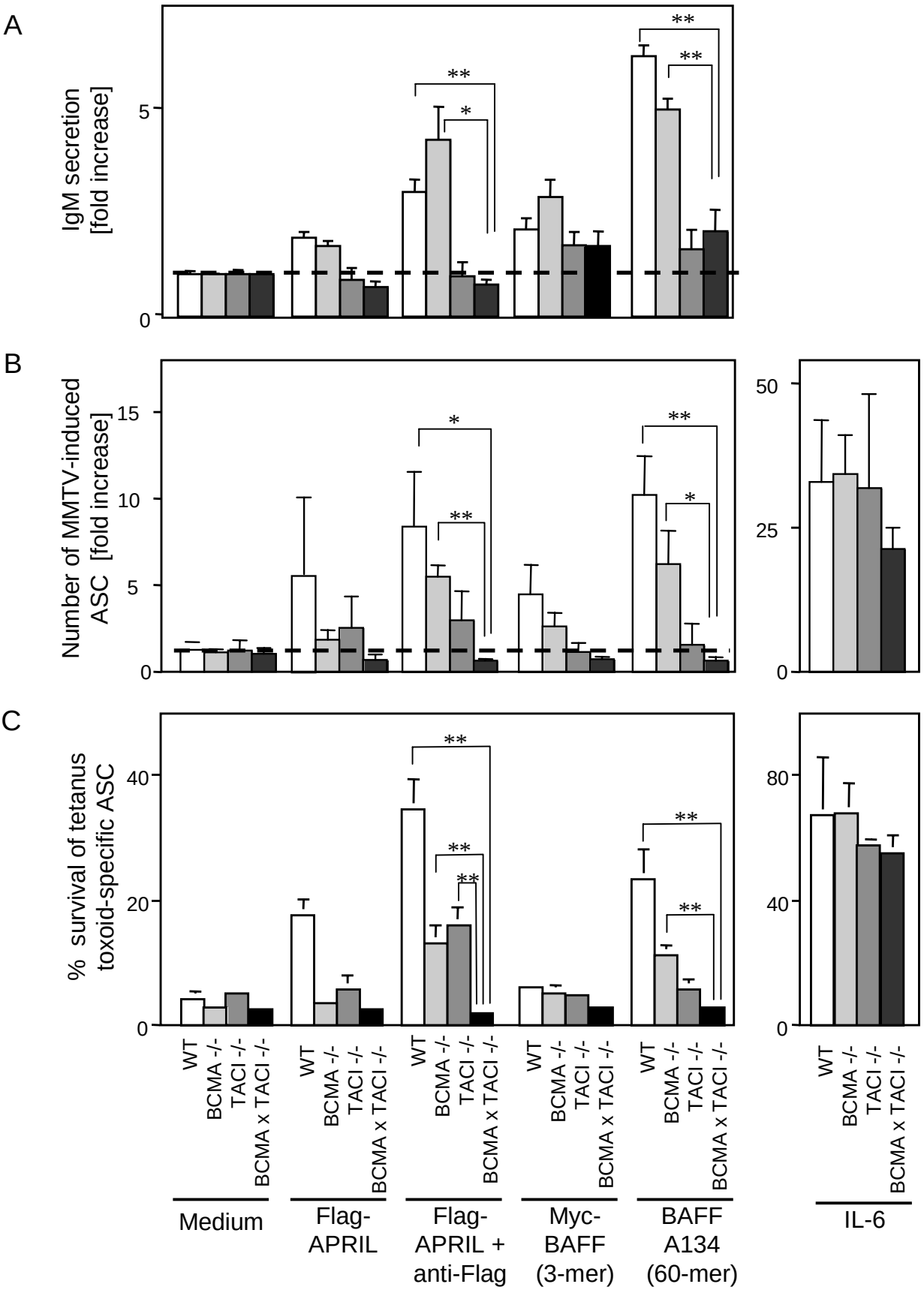

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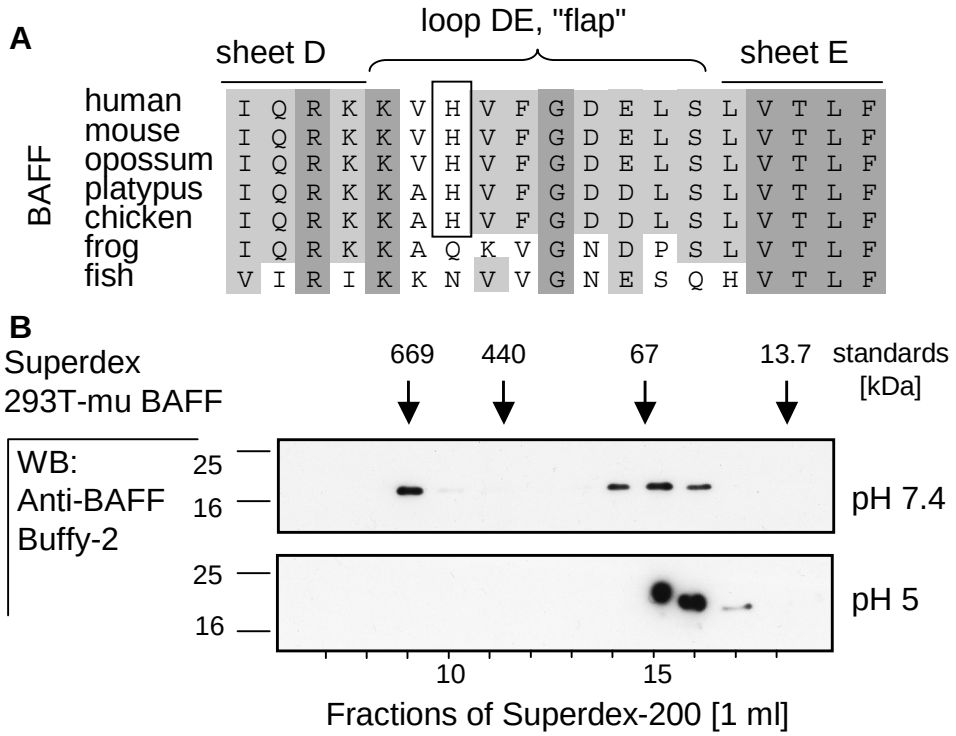
A
loop DE, "flap"
sheet D
sheet E
BAFF
human I Q R K K V H V F G D E L S L V T L F
mouse I Q R K K V H V F G D E L S L V T L F
opossum I Q R K K V H V F G D E L S L V T L F
platypus I Q R K K A H V F G D D L S L V T L F
chicken I Q R K K A H V F G D D L S L V T L F
frog I Q R K K A Q K V G N D P S L V T L F
fish V I R I K K N V V G N E S Q H V T L F
B
Superdex
293T-mu BAFF
669
440
67
13.7
standards
[kDa]
WB:
Anti-BAFF
Buffy-2
25
16
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pH 5
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Fractions of Superdex-200 [1 ml]

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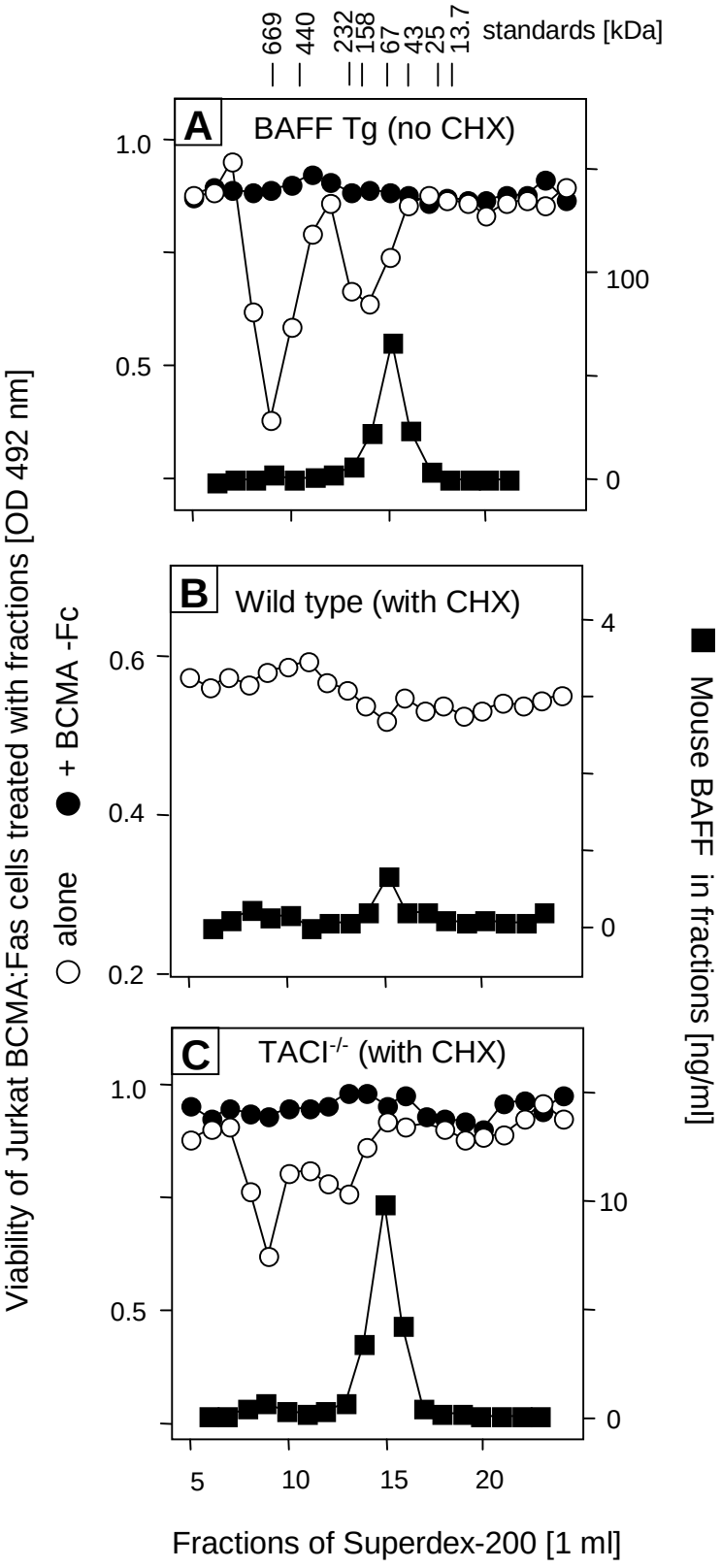
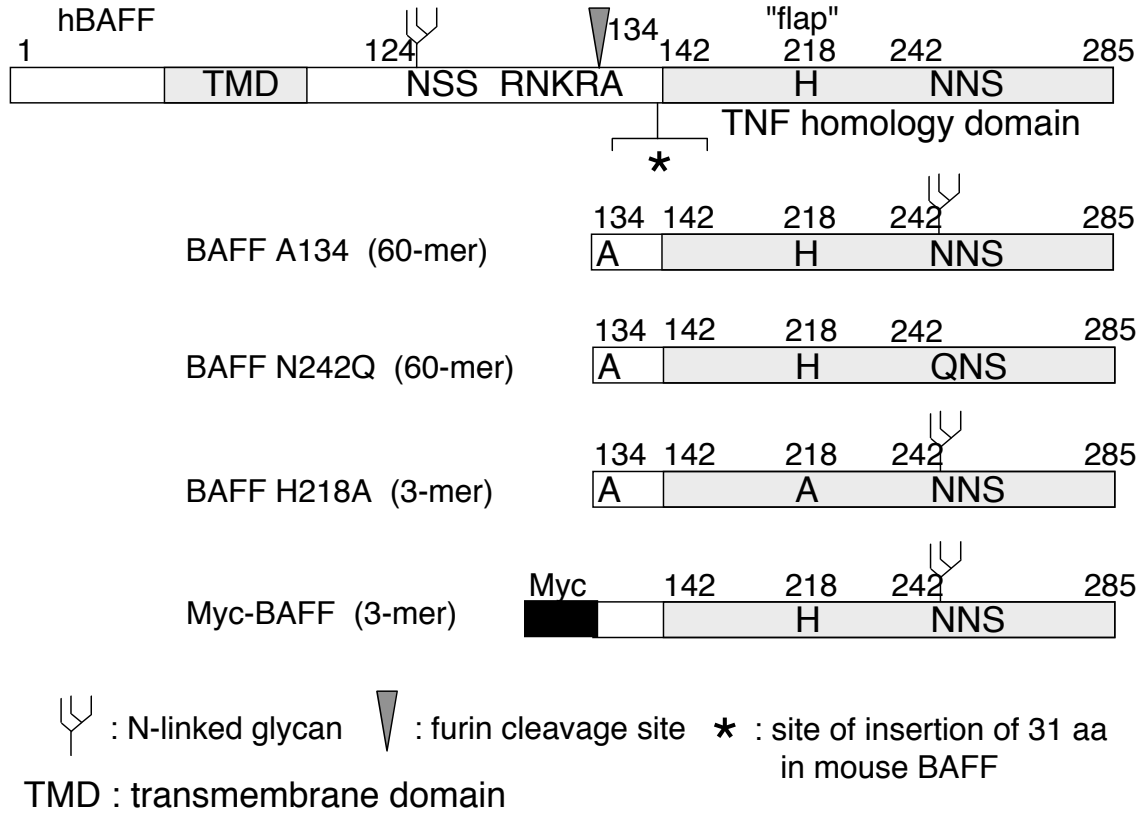
Fig 5



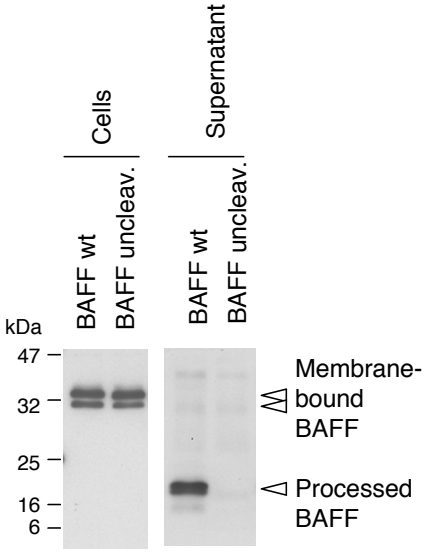
Bossen Figure 6

Online Supplemental Material

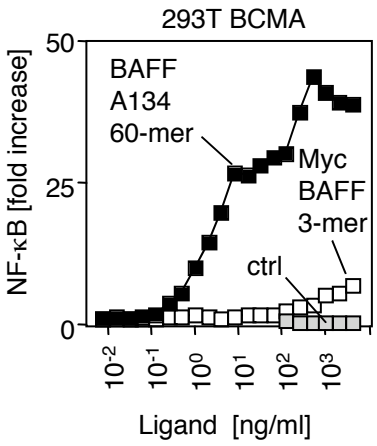
TACI, unlike BAFF-R, is solely activated by oligomeric BAFF and APRIL to support survival of activated B cells and plasmablasts. C. Bossen et al.



Supplemental Figure 1: **Schematic representation of the different recombinant BAFF used in the study**. Recombinant BAFF were characterized previously [1].

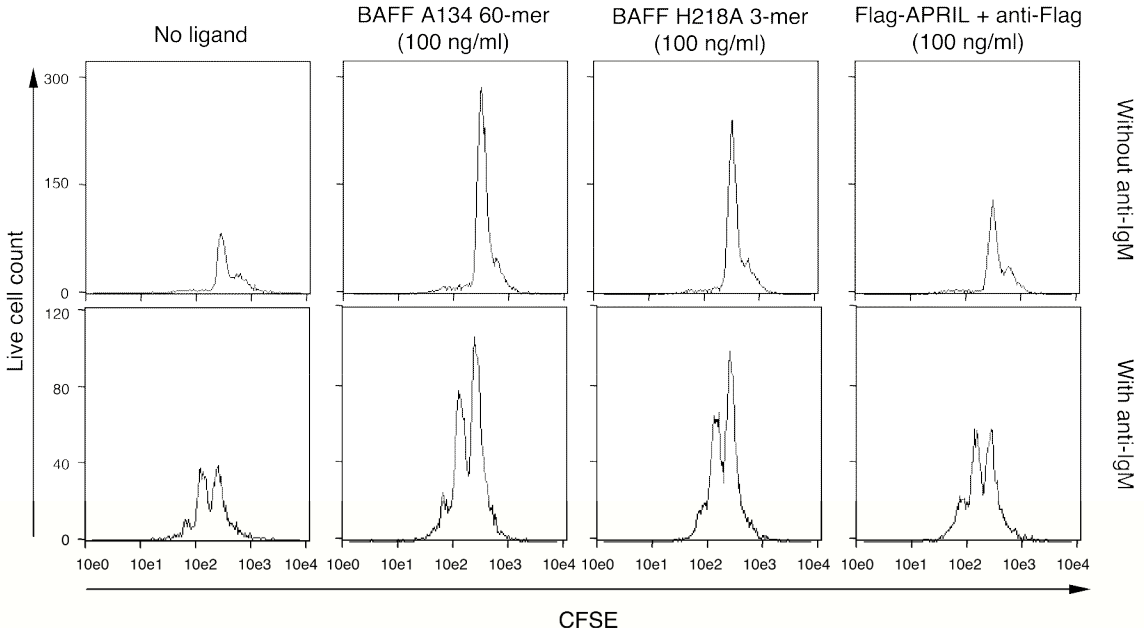


Supplemental Figure 2: **A non-cleavable form of full length mouse BAFF**.
293T cells were transfected with full length wild type mouse BAFF (BAFF wt) or full length mouse BAFF with mutations R125A and R126A in the consensus furin processing site (BAFF uncleav.). Cells and conditioned medium were harvested and analyzed by western blotting using a cross-reacting anti-mouse BAFF mAb (Buffy-2).



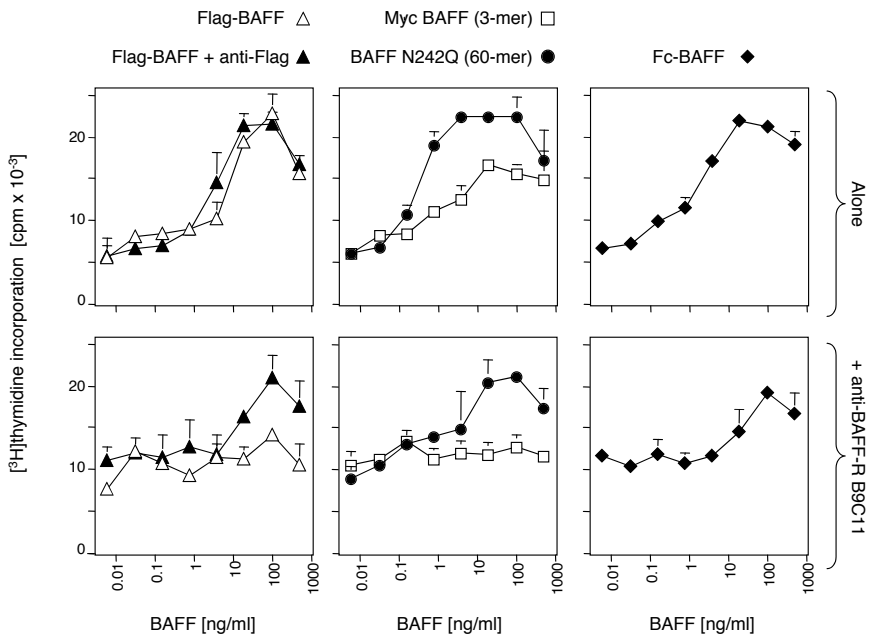
Supplemental Figure 3: **BAFF 60-mer is a potent activator of BCMA-dependent NF-κB activation.**

293T cells transiently co-transfected with full length human BCMA and NF-κB reporter plasmids were stimulated with BAFF 3-mer or 60-mer at the indicated concentrations. NF-κB activity is shown as fold induction compared to BCMA-transfected, but non-stimulated cells. BCMA transfection by itself induced a 3-fold NF-κB activation compared to control (ctrl; grey squares).

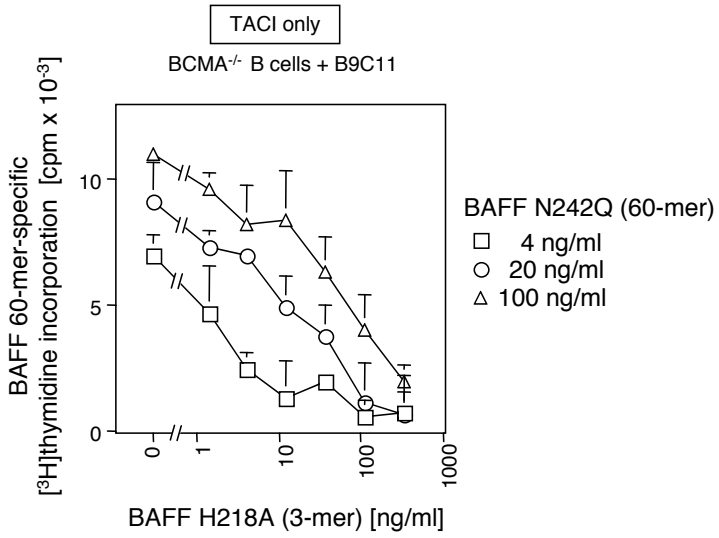


Supplemental Figure 4: **BAFF promotes survival, but not proliferation, in co-stimulation assays.**

CFSE-labelled B cells were cultured for 3 days plus or minus anti-IgM, and in the presence of the indicated ligands. Cells were analyzed by FACS (3 x 10^4 events). Histograms show the CFSE profile of cells in the live lymphocyte gate.

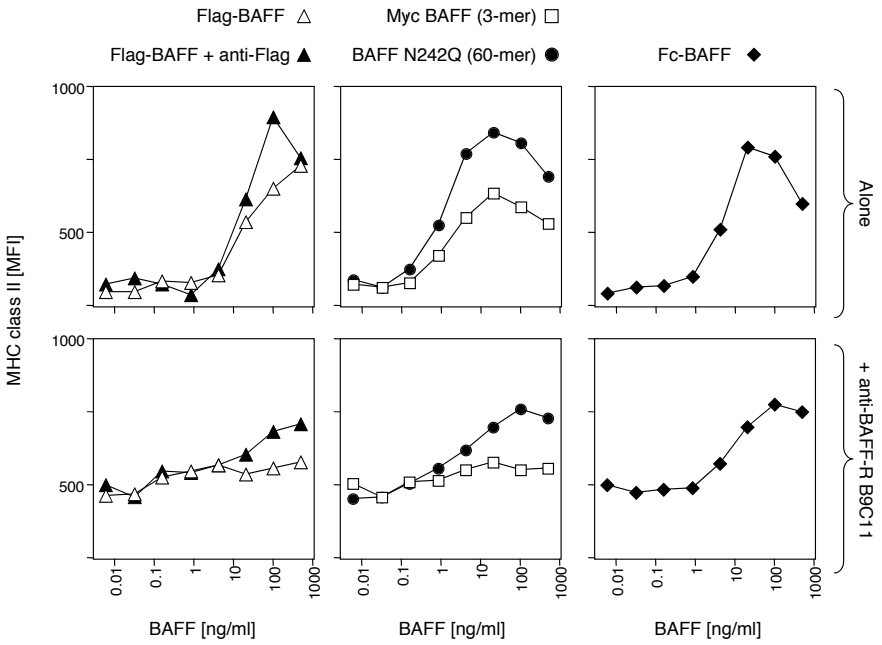


Supplemental Figure 5: **BAFF oligomers but not BAFF 3-mer co-stimulate TACI-dependent thymidine incorporation.**
Purified wild type B splenocytes were cultured under BCR-stimulating conditions, with or without anti-BAFF-R B9C11, and with the indicated concentrations of BAFF 3-mer and oligomers. After 48 h, cells were pulsed for 16 h with [^{3}H]-thymidine, harvested and counted. Points represent means ± SD of triplicate cultures.

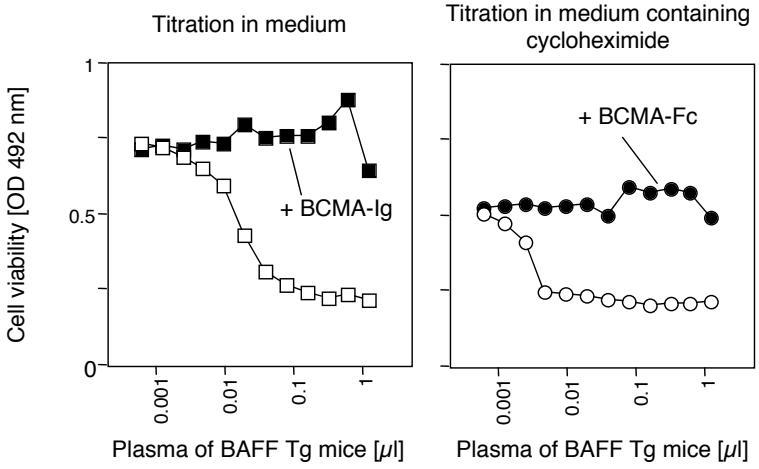


Supplemental Figure 6: **BAFF 60-mer signaling through TACI can be inhibited by an excess of BAFF 3-mer.**
Purified BCMA$^{-/-}$ B splenocytes were cultured under BCR-stimulating conditions with anti-BAFF-R B9C11, in the presence of fixed concentrations of BAFF 60-mer N242Q (0, 4, 20 or 100 ng/ml), and with the indicated concentrations of BAFF 3-mer H218A. After 48 h, cells were pulsed for 16 h with [^{3}H]-thymidine, harvested and counted. The specific effect of BAFF 60-mer is shown (Specific effect of BAFF 60-mer = thymidine incorporation with BAFF 60-mer - thymidine incorporation without BAFF 60-mer. Thymidine incorporation without BAFF 60-mer

varied form 13 to 15 x 10^3 cpm). Points represent means ± SD of triplicate cultures. Similar results were obtained with wild type B cells (data not shown).



Supplemental Figure 7: **BAFF oligomers but not BAFF 3-mer signal MHC class II upregulation in a TACI-dependent manner.**
(A) Purified wild type B splenocytes were stimulated with the indicated BAFF preparations and surface expression of MHC class II was monitored by FACS. MFI: mean fluorescence intensity. This experiment was performed in the absence of IL4 and IL6.



Supplemental Figure 8: **Enhanced sensitivity of multimeric BAFF detection using cycloheximide and Jurkat BCMA:Fas cells.**
Jurkat BCMA:Fas cells were incubated with the indicated volume of plasma from BAFF transgenic mice, in a final volume of 50 μl, and in the presence or absence of 1.5 μg/ml of cycloheximide and of 2.5 μg/ml of BCMA-Fc. Cell viability was measured after 16 h incubation with the PMS/MTS assay.

Supplemental methods.

Cells and reagents

293T cells were grown in DMEM supplemented with 10% FCS and 0.1% Na_2CO_3. Jurkat-BCMA:Fas cells (Jurkat-2309 clone 13) were cultured in RPMI, 10% FCS. Primary mouse B cells were cultured in RPMI, 10% FCS, 50 μM 2-mercaptoethanol, 5 μg/ml each penicillin and streptomycin (complete RPMI).

Generation of Jurkat-BCMA:Fas cells

Retroviruses were produced essentially as described previously [2]. Briefly, 293T cells were transiently transfected with pMSCVpuro-BCMA:Fas and co-transfected with the pHIT60 and VSV-G plasmids, containing the sequences for gag-pol and VSV-G, respectively. pMSCVpuro-BCMA:Fas encodes the signal peptide of haemaglutinin, a linker (VQCEVKLPRGS), the extracellular domain of human BCMA (amino acids 2-54), amino acids VD and the transmembrane and intracellular domains of human Fas (amino acids 169-335). After transfection, 293T cells were incubated for 24 h in RPMI supplemented with 10% FCS. Jurkat cells (10^6 cells in 1 ml) were mixed with virus-containing supernatants (3 ml) supplemented with 8 μg/ml of polybrene, left for 15 min at 37°C, and centrifuged for 1 h at 37°C and at 450 x *g* (1500 rpm). Cells were selected with 5 μg/ml of puromycin and cloned. About 40 clones were tested for their sensitivity to Fc-BAFF [3], and one of the sensitive clones (Jurkat-2309 clone 13) was selected for further experimentation.

Production of Flag-tagged APRIL.

Flag-tagged APRIL containing amino acids 92-233 of human APRIL was purified from supernatants of transiently transfected 293T cells using anti-Flag M2-agarose (Sigma). Flag-APRIL was eluted with citrate-NaOH pH 3 and neutralized with Tris-HCl pH 9. Buffer was exchanged for PBS, and the protein was stored at -70°C until use.

Immunoprecipitations:

1 μg of TACI:Fc comprising amino acids 2-118 of hTACI [4] was mixed with 250 ng of various BAFF preparations in 1 ml of PBS, immunoprecipitated with Protein A-Sepharose (GE Healthcare), and analyzed by western blotting with Buffy-2 mAb (rat IgM anti-human BAFF). The membrane was reprobed with horseradish peroxidase-coupled goat anti-human antibodies (Jackson ImmunoResearch).

Competition ELISA:

ELISA plates were coated for 16 h at room temperature with 5 μg/ml of mouse anti-human IgG (Fc)gamma fragment-specific antibody (Jackson Immunoresearch) in 50 μl of 50 mM $NaHCO_3$-NaOH, pH 9.6. Plates were blocked with PBS, 4% skimmed milk, 0.5% Tween-20 (block buffer). Subsequent incubations were done in 50μl of PBS, 0.4% skimmed milk, 0.05% Tween-20 (incubation buffer). 20 μl of cell supernatants containing BCMA-Fc (amino acids 2-54 of hBCMA) or TACI-Fc (amino acids 2-118 of hTACI) (about 50 ng) were added, followed by a fixed, optimized amount of Flag-BAFF (amino acids 137-285 of hBAFF) in cell supernatant to yield a maximal but non-saturating signal (about 50 ng/ml), in the presence of the indicated concentration of various BAFF preparations used as competitors. Binding of Flag-BAFF was revealed with biotinylated anti-Flag M2 (0.5 μg/ml) (Sigma), followed by horseradish peroxydase-conjugated streptavidin (Jackson ImmunoResearch) and ortho-phenylenediamine / H_2O_2 reagents (Sigma). Absorbance was measured at 492 nm with an ELISA reader.

Plasma collection:

200 μl of mouse blood was collected on 2 μl of 0.5 M Na-EDTA pH 8 and 2 μl of 10% $NaHCO_3$ pH 9.8, followed by centrifugation for 3 min at room temperature and at 2000 x *g*. Buffered plasma was stored frozen (or at 4°C for up to three days).

ELISA for mouse BAFF:
ELISA plates were coated for 16 h with 100 μl of 3 μg/ml of rat IgG1 anti-mouse BAFF 5A8 in PBS, blocked for 2 h with block buffer, washed and incubated for 3 h at room temperature with mouse BAFF-containing samples (150 μl or 15 μl of 1 ml Superdex fractions), or known concentration of mouse BAFF standard. Bound BAFF was revealed with 100 μl of biotinylated rat IgG1 anti-mouse BAFF 1C9 at 2 μg/ml for 2 h in incubation buffer, followed by horseradish peroxidase-coupled streptavidin (1:4000, 1h; Jackson ImmunoResearch). Peroxydase activity was measured at 492 nm with ortho-phenylenediamine reagent.

ELISA for IgM and IgA:
ELISA plates were coated for 16 h with 2 μg/ml of goat anti-mouse IgA (Caltag) or goat anti-mouse IgG + M (Caltag) in 50 mM of sodium carbonate buffer pH 9.6, blocked with block buffer, washed and incubated with cell culture supernatants (1:2 and threefold dilutions in incubation buffer) or known concentration of mouse IgM standard (Ancell). Bound antibodies were revealed with biotinylated goat anti-mouse IgA (1:2000, Caltag) or biotinylated goat anti-mouse IgM (1:2000, Jackson ImmunoResearch) followed by horseradish peroxidase-coupled streptavidin (1:4000; Jackson ImmunoResearch). Peroxydase activity was measured at 492 nm with ortho-phenylenediamine reagent.

ELISPOT:
ELISA plates were coated for 16 h with 50 μl of goat anti-mouse IgG + M (2 μg/ml; Caltag) in 50mM of sodium carbonate buffer pH 9.6, blocked for 2 h at 37°C with 300 μl of PBS + 1% BSA, washed and incubated for 6 hours at 37°C with the cell cultures (1:2 and 2-fold serial dilutions in complete RPMI), taking care not to move cells during incubation. Plates were washed. For MMTV-induced plasmablasts, spots were revealed with biotinylated goat anti-mouse IgG2a/c (1:1000 in PBS, 0.025% Tween-20, Caltag). For bone marrow plasma cells, spots were revealed with biotinylated goat anti-mouse IgG (Jackson ImmunoResearch). Biotinylated antibodies were revealed with alkaline phosphatase-coupled streptavidin (1:1000; Jackson ImmunoResearch) and finally by 5-bromo-4-chloro-3-indolyl phosphate / nitroblue tetrazolium (NCIP/ NBT) solution (Sigma).
For tetanus toxoid-specific plasmablasts, MULTIscreen HA plates (Millipore) were coated with 50μl of tetanus toxoid (10μg/ml in PBS) for 16h at 37°C, blocked for 1 h at 37°C with 200μl of RPMI, 10% FCS, washed and incubated for 5 hours at 37°C with the cell cultures (1:2 and 2-fold serial dilutions in complete RPMI), taking care not to move cells during incubation. After washing, spots were revealed with peroxydase-coupled goat anti-mouse IgG (1:1000 in PBS, 0.025% Tween-20, Zymed) and finally by 3-amino-9-ethyl carbazole (Sigma) in dimethylformamid (Sigma).

Survival assay for tetanus toxoid-specific plasmablasts
Mice of the various genotypes were mice immunized intraperitoneally with alum-adsorbed tetanus toxoid (1 Lf per mice) in the presence of CpG_{1826} (50 μg) [5]. CpG_{1826} is required to obtain efficient responses in the C57/Bl6 background. Mice were boosted 5 weeks post-immuniziation with 1 Lf of tetanus toxoid (in alum), and spleen were harvested 4 days later, at the peak of the booster response. $CD138^+$ splenic plasmablasts were purified with PE-conjugated anti-mouse CD138 (Becton Dickinson) and anti-PE magnetic beads (Miltenyi Biotech). Purified plasmablasts ($5x10^4$/well in 200 μl of complete RPMI containing only 1.4 % FCS) were incubated for 44 hours with different ligands at 500 ng/ml or IL-6 at 10 ng/ml. Number of viable plasmablasts were analyzed at day 0 and day 2 by tetanus toxoid-specific ELISPOT [6].

NF-κB reporter assay:
NF-κB assays were performed essentially as described [7]. 293T cells were seeded overnight in 96 well plates in 100 μl of

DMEM, 10% FCS. Cells were transfected using PolyFect transfection reagent (Qiagen) with 70 ng/well of a plasmid mix containing a NF-κB luciferase reporter plasmid (7.5 ng), a renilla luciferase plasmid for normalization (7.5 ng), an EGFP tracer plasmid (7.5 ng), a plasmid encoding full length hBCMA (20 ng) and an empty plasmid (22.5 ng). 8 h later, medium was exchanged for fresh DMEM supplemented with 10% FCS and the indicated concentration of myc-BAFF (3-mer) or BAFF A134 (60-mer). After 24 h, cells were lyzed and firefly and renilla luciferase activities were quantified with dual luciferase reporter assay system (Promega) and a TopCount-NTX luminometer (Packard).

Splenocyte co-stimulation assay:
Splenic B cells were isolated with anti-B220 magnetic beads according to the provider's instructions (Miltenyi Biotech). Purified B cells ($3x10^5$/well in 200 μl of complete RPMI) were grown for 48 h with 2 μg/ml of goat F(ab')2 anti-mouse μ chain antibody (Jackson ImmunoResearch) and in the presence of serial dilutions of various ligands. Where indicated, BAFF 3-mer was added as a competitor for BAFF 60-mer. When required, anti-Flag M2 antibody (1 μg/ml) or anti-BAFF-R B9C11 (0.5 μg/ml) were added. Cells were pulsed for an additional 16-18 h with 1 μCi/well of tritiated thymidine, harvested and counted in a TopCount-NTX liquid scintillation counter (Packard).
In some experiments, purified B cells at 10^6 cells/ml were stained for 10 min at 37°C with CFSE at 1 μg/ml in PBS prior to cultivation. These cells were analyzed using a three-color FACScan flow cytometer (Becton Dickinson, San Jose, CA) and FlowJo software (Tree Star, Inc.). Viable cells were differentiated from dead cells by the FSC/SSC profile.

MHC class II upregulation assay:
Purified splenic B cells ($3x10^5$/well in 200 μl of complete RPMI, supplemented or not with 0.2 ng/ml each IL-4 and IL-6) were grown for 66 h in the presence of the indicated ligands, stained with FITC-conjugated anti-mouse MHC class II Ia+Ie (Becton Dickinson) and analyzed by FACS.

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