B cell depletion in immune thrombocytopenia reveals splenic long-lived plasma cells.
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Primary immune thrombocytopenia (ITP) is a disorder caused by autoantibody-mediated platelet destruction and decreased platelet production. Rituximab, a B cell–depleting agent, has become the first-line treatment for ITP; however, patients with refractory disease usually require splenectomy. We identified antibody-secreting cells as the major splenic B cell population that is resistant to rituximab. The phenotype, antibody specificity, and gene expression profile of these cells were characterized and compared to those of antibody-secreting cells from untreated ITP spleens and from healthy tissues. Antiplatelet-specific plasma cells (PC) were detected in the spleens of patients with ITP up to 6 months after rituximab treatment, and the PC population displayed a long-lived program similar to the one of bone marrow PC, thus explaining for most of these patients the absence of response to rituximab and the response to splenectomy. When analyzed by multiplex PCR at the single-cell level, normal splenic PC showed a markedly different gene expression profile, with an intermediate signature, including genes characteristic of both long-lived PC and proliferating plasmablasts. Surprisingly, long-lived PC were not detected in untreated ITP spleens. These results suggest that the milieu generated by B cell depletion promotes the differentiation and settlement of long-lived PC in the spleen.

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body-secreting cells (ASCs) from HDs and from patients treated or not with rituximab, revealed striking differences between these different entities and challenged the accepted views of the environmental conditions that permit the differentiation and residence of long-lived PC.

Results

Patients with ITP. Characteristics of 15 splenectomized patients with ITP, treated or not with rituximab, are presented in Supplemental Table 1 (supplemental material available online with this article; doi:10.1172/JCI65689DS1). Ten patients, with a median age of 40 years (range, 26–74 years), received 4 weekly infusions of 375 mg/m² rituximab. All were nonresponsive to rituximab, with platelet counts below 30 × 10⁹/1 or lower than the double of the baseline count in the month preceding splenectomy. They were splenectomized in the 3 to 6 months following the last rituximab infusion. Four of them received intravenous Ig (IV Ig) in the 1–3 weeks preceding the splenectomy. Seven out of ten presented with a complete response, with a follow-up of 7 to 24 months after splenectomy. Five patients with ITP were not treated with rituximab and were splenectomized after a median ITP duration of 24 months. Two of them received IV Ig 2 weeks before splenectomy. All were responsive to the splenectomy, with a follow-up of 18 to 30 months. The term “ITP” will be used hereafter for patients not treated with rituximab unless otherwise stated.

The spleen in ITP is the site of an active B cell response. We first investigated the presence of ASCs and germinal center (GC) B cells as hallmarks of an active immune response in the spleens of patients with ITP not treated with rituximab (Figure 1A and Supplemental Table 2). The major part of the ASC population in these patients expressed the Ki67 cell cycle marker and were HLA-DR hi, i.e., displayed a PB phenotype. Overall, PB were markedly increased in the spleens of these patients (Figure 1B). PC were slightly but not significantly increased compared with healthy donors (HDs) (Figure 1C). Similarly, the GC B cell population was also significantly expanded in these ITP spleens (Figure 1D). By confocal microscopy analysis, we found numerous GC structures within secondary follicles in all ITP spleens examined (n = 3) (Figure 1E), whereas mainly primary follicles were observed in splenic samples from HDs (n = 3) (Figure 1F). PB were found in these ITP spleens (Figure 1, G and H) but were rarely detectable in HDs, with a wide distribution from the GC area to the red pulp. Numerous proliferating T cells were also observed in the patient with ITP and not in the HD (Figure 1, I and J). Altogether, our data indicate that the spleen is the site of an unusually active B cell response in patients with ITP.

Presence of anti-GpIIbIIIa IgG-producing cells in ITP spleens. We next investigated the ability of ASCs to produce autoantibodies in vitro. We used the previously described anti-GpIIbIIIa ELISPOT assay in order to quantify the fraction of autoreactive ASCs (9). In all but one spleen, we observed GpIIbIIIa-specific spots, ranging from 0.5% to 1.2% of total IgG-secreting cells (Figure 1K and Supplemental Table 2). No anti-GpIIbIIIa IgG-secreting cells were observed in HDs (Figure 1L). After a 5-day culture of ITP spleens without stimulation, anti-GpIIbIIIa IgG-secreting cells were still observed with an increase of the size and the intensity of the spots (data not shown), reflecting the robustness of the response. All patients responded to the splenectomy, including the one showing a negative anti-GpIIbIIIa IgG ELISPOT.

Splenic residual B cells in patients with primary failure of rituximab are mainly PC and some of them are autoreactive. In order to study the residual B cells that survived the rituximab-suppressive action, we focused on rituximab-treated patients who did not respond and had been subsequently splenectomized within the 3–6 months after the last rituximab infusion, i.e. before the reemergence of newly formed B cells.

As extensively described, B cells were scarcely detectable in peripheral blood (<0.1% of CD45+ cells) (Table 1). We did not observe any dividing Ki67+ cells; all cells expressed the CD27 marker, and more than 50% expressed IgA isotypes as previously described (data not shown) (22). By contrast, analysis of the 10 spleens from rituximab-treated patients revealed that 0.5% of CD45+ mononuclear cells were B cells (Table 1). Further analysis showed that these rituximab-resistant B lineage cells could be separated in two populations: memory B cells and PC (Figure 2A). No dividing Ki67+ cells were observed. In all but one rituximab-treated patient, PC were the main residual population (Figure 2B). As described for normal splenic samples (4), splenic PC from rituximab-treated patients (RTX-PC) did not express CD138 in contrast with bone marrow PC and did not downregulate CD19, as 92%–98% of CD27+CD38hi cells were CD19+. RTX-PC were characterized as CD38hiCD20+Ki67−HLA-DR+CD9+ cells (Figure 2A) and expressed splenic PC surface markers, such as CD86 and CD11a (ref. 4 and Supplemental Figure 1A). Patients who responded to splenectomy (7 out of 10) tended to have a higher number of PC in the spleen, as compared with nonresponders (Figure 2C), although this difference failed to reach significance due to the small number of patients in each category (P = 0.066).

We used the ELISPOT assay to determine whether some residual PC were autoreactive (Figure 2C). Residual PC expressed IgM, IgG, and IgA isotypes (Supplemental Figure 1B). We observed anti-GpIIbIIIa IgG-secreting cells in 7 out of 10 patients, with a frequency ranging from 0.25% to 4%, but we failed to identify anti-GpIIbIIIa IgM- or IgA-secreting cells (Table 1). Six out of these seven patients presenting GpIIbIIIa-specific PC responded to the splenectomy, while specific spots were detectable in a patient who failed to respond (Figure 2, D and E).

Overall, these findings suggested that the failure of rituximab treatment could be explained in the majority of the patients by the presence of residual autoreactive anti-GpIIbIIIa PC in the spleen.

Residual PC in patients with primary failure of rituximab display a long-lived genetic program. In patients with a primary failure of rituximab, the persisting splenic B cells are nondividing and contain minimal numbers of memory B cells, thus suggesting that the residual PC observed have been generated before the rituximab-induced depletion and were thus long lived. To test this hypothesis, we performed a transcriptome analysis to compare the gene expression profiles of the various splenic ASC subsets from patients and controls. We sorted PC and PB from 3 HDs and 3 patients with ITP, using HLA-DR expression to discriminate between them (gating strategy: Supplemental Figure 2), as well as PC from 4 rituximab-treated patients. We first focused on the 2 major subsets from patients, i.e., PB from patients with ITP (ITP-PB) and RTX-PC, which could be sorted to high purity due to their predominance in each category of patients. We performed a supervised analysis and identified 609 differentially expressed genes (P < 0.05, > 4-fold change). The genes overexpressed in RTX-PC compared with those in ITP-PB were antiparlotin genes (BCL2, CFLAR, TNFAIP3, BIRC3); negative regulators of the cell cycle and notably several members of the family of Kruppel-like factors (KLF2, KLF6, KLF9, KLF15); transcription factors (FOS, JUN, JUNB, RORA); genes related to the
Figure 1
Spleen in ITP is the site of an active B cell response producing anti-GpIIbIIIa–specific ASCs. (A) Flow cytometry analysis of splenic mononuclear cells labeled with antibodies to CD19, CD38, CD20, CD24, HLA-DR, and Ki67. After gating on CD19+ cells, ASCs were identified as CD20-, CD24-, CD38hi (blue); PB were identified as CD20-, CD24-, CD38hi, HLA-DR+, Ki67+ (red); and GC B cells were identified as CD20+, CD24-, CD38+, Ki67+ (green). (B–D) Numbers of splenic (B) PB, (C) PCs (identified as CD19+CD20–CD24–CD27+CD38hiKi67–), and (D) GC B cells in patients with ITP (n = 5) compared with HD (n = 8). (E–J) Analysis by confocal microscopy of spleen sections from a patient with ITP (ITP1) and a HD (17 years old) using anti-CD3, anti-CD20, anti-Ki67, and anti-IgL (anti-κ/λ light chains) antibodies. (E) Secondary follicles with proliferating GC B cells, (G, box enlarged in H) PB (CD20-, Ig κ/λ+, Ki67+), and (I, box enlarged in J) T cells (CD3+Ki67+) in patient with ITP and (F) primary follicles in HD. Scale bars: 100 μm (E–G and J); 5 μm (H and J). Data are representative of 3 ITP and HD samples. (K) ELISPOT quantification of anti-GpIIbIIIa IgG-secreting cells in 3 ITP (top) and 1 HD (bottom left) among total IgG-secreting cells (bottom middle), with KLH as antigen control (bottom right). (L) Frequency of anti-GpIIbIIIa IgG-secreting cells in patients with ITP (n = 5) compared with HD (n = 4). Two-tailed Mann-Whitney tests (**P < 0.001; *P = 0.044). Symbols indicate individual samples; horizontal bars represent mean values (± SEM).
unfolded protein response (Dnaj, HSPB1, MAFF, ATF3); and genes encoding adhesion molecules or surface receptors (ICAM1, CD9, IL5R, IL6ST). On the other hand, RTX-PC underexpressed, as compared with ITP-PB, genes implicated in positive regulation of the cell cycle (BIRC5, CENPF, CEB1, ZWINT, MCM4, MKI67); genes encoding adhesion molecules (SIPR1, CD58); and activating molecules like TLRs (TLR10, TLR7) (Figure 3). Thus, RTX-PC expressed a specific genetic program consistent with a quiescent, long-lived phenotype.

The gene expression profile of PC from HDs differs from the one of RTX-PC. PB from patients with ITP and PC from rituximab-treated patients represent two opposites of the ASCs differentiation pathway. To position PC from HDs along this maturation scale, we compared the gene expression profile of PC from HDs to that of both ITP-PB and RTX-PC for the 609 discriminating genes described previously (Figure 3). For 267 of these genes, the expression was similar between RTX-PC and HD-PC, while for 99 of them, HD-PC expression was similar to that of ITP-PC (<2-fold change).

Among the genes shared by HD- and RTX-PC were upregulated HD-PC expression was similar to that of ITP-PB (<2-fold change). The major fraction of HD-PC showed an intermediate profile that differed from that of RTX-PC and ITP-PB. A few cells clustered with the RTX-PC or ITP-PB population. We then selected 8 genes for further analysis: 4 cell cycle genes (BUB1, MKI67, ZWINT, CENPF, highly expressed in ITP-PC and at background level in RTX-PC) and 4 cell cycle regulators/antiauxototopic genes (KLF6, KLF9, TNFAIP3, AT3, highly expressed in RTX-PC and expressed at a lower level in ITP-PC). Similar results were obtained for the PCA using this set of genes (Figure 4B). Based on their qualitative expression, we further classified each single cell with a “PB signature” (>1 cell cycle gene and ≥1 upregulated PC genes) or a “PC signature” (no cell cycle gene and ≥1 upregulated PC genes) or as “unclassified.” These differential criteria were selected to match the transcriptional characteristics of the genes in the 2 categories: an on/off expression for cell cycle genes and a low/high expression for PC-specific genes in ITP-PC vs. RTX-PC. According to these criteria, 84% of RTX-PC showed a “PC signature” and 75% of ITP-PB showed a “PB signature.” In contrast, 75% of individual HD-PC were “unclassified,” with a “PC signature” identified for less than 15% of them (Figure 4C). Thus, RTX-PC are a unique long-lived population from which the major part of HD-PC differ.

IITP-PC analyzed at the single-cell level do not display a long-lived program. To ask whether the presence of long-lived PC in rituximab-treated spleens could be contributed to by the autoimmune inflammatory environment, we analyzed PC from patients with ITP (not treated with rituximab) using the same single-cell multiplex PCR approach. PCA based on the expression profile of the 15 genes described previously indicated that, as for HD-PC, the PC present in patients with ITP showed an intermediate phenotype between long-lived PC and proliferating PB (Figure 4D). It seems therefore that the generation of the long-lived PC in spleens of rituximab-treated patients does not result from a previous inflammatory state.

Spleenic ASC from patients with ITP display a specific genetic signature characterized by downregulation of SOCS3. To identify disease-spe-
specific genes, we extracted 158 probes that discriminated all patient subsets (ITP-PC \( n = 3 \), ITP-PB \( n = 3 \), and RTX-PC \( n = 4 \)) from control subsets (HD-PC \( n = 3 \) and PB \( n = 2 \)) ( \( >2 \)-fold change, \( P < 0.01 \)). The 12 most striking genes are shown in Figure 5A. ASC in HDs overexpressed SOCS3 as well as PTP4A3 (also known as PRL-3; involved in CXCL12-mediated migration of multiple myelomas, and, together with SOCS3, defining a multiple myeloma subtype) (23), in contrast with ASC from patients with ITP that expressed both genes minimally (a 50-fold difference). RT-PCR confirmed that low expression of SOCS3 is a hallmark of ITP ASC (Figure 5B). Contradictory data have been reported concerning the impact of SOCS3 on cell migration. Two groups described a negative feedback control of SOCS3 on the CXCR4 signaling function (24, 25); on the other hand, Tarlinton and colleagues, while reporting a prolonged STAT3 signaling induced by IL-6 stimulation of SOCS3-deficient PC, observed no impact.

Figure 2

Autoreactive PC in patients with primary failure of rituximab. (A) Flow cytometry analysis of splenic mononuclear cells, labeled with anti-CD19, CD38, CD20, CD24, CD27, CD9, HLA-DR, and Ki67 antibodies. All residual splenic B cells were CD19+CD27+ and included memory B cells (CD24−CD38+) and PC (CD24−CD38hi) (blue gate), further identified as CD20+HLA-DR+Ki67−CD9+. (B) Percentage of PC per CD19 cells for each patient (mean, 74.9% [range, 33–98%]). (C) Absolute numbers of spleen PC in rituximab-treated patients, segregated as responders and nonresponders to the splenectomy. Two-tailed Mann-Whitney test (\( P = 0.066 \)). (D) Frequency of anti-GpIIbIIa IgG-secreting cells in responders or nonresponders to the splenectomy. Two-tailed Mann-Whitney test (\( P = 0.64 \)). (E) ELISPOT quantification of anti-GpIIbIIa IgG-secreting cells in 2 rituximab-treated patients among total IgG-secreting cells, with KLH as antigen control, estimated from \( 1 \times 10^6 \) total spleen cells (RTX1 and RTX2) or \( 2 \times 10^4 \) cell-sorted PC (RTX2, sorting of CD19+CD27−CD38hi cells). The dilution factor is indicated for IgG-positive spot detection. Symbols indicate individual samples; horizontal bars represent mean values (± SEM).
of SOCS3 gene inactivation on CXCL12-induced migration of mouse B cells (26). Interestingly, a higher expression of the CXCR4 gene was observed in ASC from patients with ITP compared with those from HD (Figure 5A), but cell surface expression of CXCR4 was similar between them (data not shown).

RTX-PC are nonmigratory cells that display a resident phenotype. In order to find out whether the overexpression of CXCR4 and downregulation of SOCS3 and PRL-3 may have an impact on PC or PB migration toward CXCL12, we studied ASC migration by culturing total spleen cells with or without CXCL12. We observed that 30% of ASC migrated toward CXCL12 in ITP samples and 20% of ASC migrated toward CXCL12 in control samples, with a fraction of cells migrating without cytokines, as previously described (ref. 27 and Figure 5C). The migratory population expressed high levels of HLA-DR at the surface, suggesting that it had a PB phenotype (data not shown).

By contrast, RTX-PC were non migratory toward CXCL12, whatever the duration of cell culture (6, 12, 24 hours). RTX-PC did not express CXCR3, CD62L, or CCR10 (data not shown) but expressed CCR2, the receptor for CCL2 (see below), and the adhesion molecules CD44, CD11a, and CD9 (Supplemental Figure 1A). RTX-PC are thus nonmigratory and display a resident phenotype.

ASC survival in ITP is increased, suggesting a role for the proinflammatory environment. We next wanted to assess whether the genetic signature observed could be correlated to the inflammatory ITP microenvironment. Both ASC from rituximab-treated patients and patients with ITP showed an increased survival compared with that of ASC from HD upon in vitro culture (P < 0.01) (Figure 6A). If the better persistence of ASC from rituximab-treated spleens is likely to reflect their intrinsic survival capacity in vitro, it might rather correspond, for ITP-PB, to a maintenance contributed by proliferation. We next investigated whether specific cytokines could be involved and released in the culture medium. In a panel of 27 cytokines, we did not observe a bias for TH1 or TH2 cytokines, either in ITP or rituximab-treated patients (data not shown). By contrast, BAFF secretion was increased 2 fold in rituximab spleen supernatants compared with that in ITP spleens (P < 0.05) (Figure 6B); IL-6 was increased in 3 out of 4 ITP spleens compared with controls but not in rituximab samples (P < 0.05) (data not shown). There was no difference in APRIL secretion in rituximab and/or ITP spleen supernatants compared with those from HD (data not shown). CCL2 (also known as MCP-1) was significantly increased in both ITP and rituximab spleen cultures compared with that in HD cultures (Figure 6C), and its receptor, CCR2, was expressed at the RTX-PC surface. CCL2 has been shown to recruit monocytes, neutrophils, or basophils at inflammation sites. Accordingly, among other cell types tested, basophils numbers were increased in rituximab (P < 0.01) and in ITP (P < 0.05).
BIRC5 and ITP-PB (on RTX-PC, ITP-PB and HD-PC using 15 genes showing differential expression between RTX-PC and ITP-PB). Multiplex single-cell PCR was performed with the Fluidigm Dynamic Array on RTX-PC, ITP-PB and HD-PC using 15 genes showing differential expression between RTX-PC and ITP-PB (BIRC5, BUB1, MKI67, ZWINT, CDC6, CCND2, CENPF, KLF6, KLF9, FOS, TNFAIP3, BIRC3, ATF3, CD9, SOCS1). Cells expressing less than 2 genes were excluded from the final analysis. (A) 3D representation of the PCA of 504 single cells analyzed according to these 15 genes. Each dot represents a single cell: red, ITP-PB; yellow, RTX-PC; blue, HD-PC. The Ct value was normalized for each cell with B2M. (B) 3D PCA view of the same samples according to the expression of 8 genes: 4 “PB genes” (cell cycle genes: BUB1, MKI67, ZWINT, CENPF), highly expressed in ITP-PB and at background level in RTX-PC, and 4 “PC genes” (KLF6, KLF9, TNFAIP3, ATF3), highly expressed in RTX-PC and expressed at a low level in ITP-PB. (C) A simplified classification of each cell analyzed using the 8 genes defined above to classify cells with a “PB signature” (>1 cell cycle gene and ≤1 PC genes) or a “PC signature” (no cell cycle gene and >1 PC genes) or as “unclassified.” (D) 3D PCA view of ITP-PC together with ITP-PB and RTX-PC analyzed according to the 15 genes defined above.

**Figure 4**
The intermediate gene expression profile of HD-PC and ITP-PC compared with RTX-PC and ITP-PB is a cell-intrinsic characteristic. Multiplex single-cell PCR was performed with the Fluidigm Dynamic Array on RTX-PC, ITP-PB and HD-PC using 15 genes showing differential expression between RTX-PC and ITP-PB (BIRC5, BUB1, MKI67, ZWINT, CDC6, CCND2, CENPF, KLF6, KLF9, FOS, TNFAIP3, BIRC3, ATF3, CD9, SOCS1). Cells expressing less than 2 genes were excluded from the final analysis. (A) 3D representation of the PCA of 504 single cells analyzed according to these 15 genes. Each dot represents a single cell: red, ITP-PB; yellow, RTX-PC; blue, HD-PC. The Ct value was normalized for each cell with B2M. (B) 3D PCA view of the same samples according to the expression of 8 genes: 4 “PB genes” (cell cycle genes: BUB1, MKI67, ZWINT, CENPF), highly expressed in ITP-PB and at background level in RTX-PC, and 4 “PC genes” (KLF6, KLF9, TNFAIP3, ATF3), highly expressed in RTX-PC and expressed at a low level in ITP-PB. (C) A simplified classification of each cell analyzed using the 8 genes defined above to classify cells with a “PB signature” (>1 cell cycle gene and ≤1 PC genes) or a “PC signature” (no cell cycle gene and >1 PC genes) or as “unclassified.” (D) 3D PCA view of ITP-PC together with ITP-PB and RTX-PC analyzed according to the 15 genes defined above.
lived PC in rituximab-treated patients, we provided for the first time in humans, the comparison of the two opposite sides of the in vivo ASC genetic program. Splenic RTX-PC presented a bona fide long-lived program very similar to the one of bone marrow PC, characterized by a strong expression of antiapoptotic factors and of negative regulators of the cell cycle, including multiple members of the Krüppel-like factor family, of the AP-1 family, and of genes involved in the unfolded protein response (30–34). In contrast, PB overexpressed positive regulators or markers of the cell cycle.

When compared with RTX-PC, surprisingly, normal splenic PC displayed an intermediate profile with the expression of some antiapoptotic genes shared with long-lived PC and some cell cycle genes expressed by PB. To unravel whether normal PC were a mixture of several populations or represented a distinct PC differentiation stage, their transcriptomic profile was analyzed at the single-cell level and compared with single PC and PB isolated from patients with ITP, treated or not with rituximab. Based on a small group of genes differentially expressed by PB or long-lived PC, this analysis showed that most of the normal splenic PC showed a genetic profile with a mixed PC and PB signature. Interestingly, PC from patients with ITP not treated with rituximab also displayed, at the single-cell level, an intermediate phenotype with the expression of long-lived PC and PB genes, suggesting that the inflammatory environment of the ITP spleen does not favor the formation of PC with a long-lived phenotype.

The gene expression profiles described here are intriguing because they suggest at first that normal splenic PC may display some characteristics of a long-lived program, while keeping at the same time the capacity to enter into proliferation. Such cellular divisions have never been described for PC, but they may occur at a very low rate in defined hemostatic situations. Whether these PC that have kept some PB characteristics can still migrate to other lymphoid sites also remains an open question (29). These data also suggest that the human spleen in an autoimmune inflammatory environment is not a niche for long-lived PC. An alternative explanation for the absence of long-lived splenic PC in the ITP setting could be the ongoing production of PB and PC that would prevent their local accumulation. Our observation seems to differ from the one in lupus-prone NZBxNZW mice, in which splenic PC, which are in large excess as compared with control animals (5), have differentiated into long-lived PC in the absence of any B cell–depleting therapy. In the human autoimmune setting that we described, which may be quite different from the previous mouse model in which there is a genetic predisposition for an ongoing autoimmune reaction, the total number of PC is in fact within the same range in ITP and rituximab-treated spleens. This result argues against the survival of a few PC present in ITP spleen that would already possess the long-lived characteristics but rather suggests that the rituximab-treated human spleen in ITP provides a unique environment in which rituximab-resistant ASC can differentiate into bona fide long-lived PC. Interestingly, B cell depletion in healthy mice, either by irradiation (2) or by anti–B cell antibody treatment (35), also triggered the establishment of splenic long-lived PC, suggesting that it is possibly the absence of B cells and the resulting excess of accessory cells or cytokines necessary for PC survival, such as BAFF (see below), which may be responsible for this phenomenon. These results may bear some clinical relevance, since they would suggest that treatment with rituximab may paradoxically induce in certain situations the differentiation of autoimmune PC into long-lived resident cells.

Stromal cells, eosinophils, and megakaryocytes secreting CXCL12, IL-6, and APRIL have been shown to interact with long-lived PC in bone marrow, and IL-6–secreting basophils and stromal cells have been shown to interact with PC in the spleen (27, 36–41). A specific inflammatory milieu could promote the residence of long-lived PC in rituximab-treated patients, since RTX-PC survived better than control ones upon in vitro incubation of total splenic cells. A multiplex cytokine analysis of these culture supernatants revealed an increase in secretion of CCL2, a chemokine with the potential to attract monocytes, neutrophils, and basophils (42, 43), an increase that was, however, common to the ITP and rituximab treatment conditions. Accordingly, basophil numbers were markedly enhanced in both cases. The
...and PB production in the ITP spleen, also described in many other target organs of human autoimmune diseases, since only a small percentage of the PC produced seem to secrete autoantibodies? As recently highlighted, inflammatory B cells producing cytokines such as IL-6 may promote this local B cell activation, but the mechanism of tolerance breakdown remains unknown (46). Finally, a straight forward proposition coming out of these results is that ITP may be caused either by autoimmune CD20+ memory B cells and the short-lived PB and PC they produce (response to rituximab) or by long-lived CD20+ pathogenic PC present in the spleen (response to splenectomy after rituximab failure) or in other lymphoid niches (47) (failure of both treatments). One future therapeutic goal in ITP could be, according to our results, to modulate splenic long-lived PC in the rituximab-treated spleen. BAFF concentration was estimated by ELISA in culture medium of 10^6 spleen cells cultured in triplicates for 5 days (mean BAFF concentration, RTX: 33.6 ± 6.2 pg/ml; ITP: 7.2 ± 1.2 pg/ml; HD: 20.2 ± 1 pg/ml). (C) CCL2 concentration in spleen supernatants after 5-day culture. CCL2 concentration was estimated by a multiplex 27-cytokine assay in spleen supernatants of 10^6 cells cultured in triplicate for 5 days (mean CCL2 secretion, RTX: 11,410 ± 228 pg/ml; ITP: 11,410 ± 1,236 pg/ml; HD: 3,233 ± 1,927 pg/ml). (D) Number of basophils in ITP and rituximab spleens. Spleen basophils were estimated by flow cytometry as numbers of HLA-DR–CD123–FcyRI+ cells per 10^6 cells (mean basophil numbers, RTX: 1,162 ± 79.8; ITP: 591 ± 178.4; HD: 201 ± 64.5). (E) ASC survival from HD spleens after culture with or without BAFF (100 ng/ml). Survival was estimated as in A. The values obtained with or without BAFF for each sample are connected by a straight line (median fold increased survival with BAFF: 8.3 [3.2–23]). Significant differences estimated by Mann-Whitney and paired t test (**P < 0.01, *P < 0.05). Symbols indicate individual samples; horizontal bars represent mean values (± SEM).

Figure 6
ASC in ITP display a prolonged in vitro survival within a specific cytokinic and cellular microenvironment. (A) ASC survival after 5-day culture. Survival was estimated by the fraction of input ASC detectable after 5-day culture of 5 × 10^6 spleen cells in triplicate, estimated by an anti-Ig ELISPOT (mean survival, RTX: 26.4% ± 3.7%; ITP: 32% ± 9.5%; HD: 9.3% ± 1.6%). (B) BAFF concentration in spleen supernatants after 5-day culture. BAFF concentration was estimated by ELISA in culture medium of 10^6 spleen cells cultured in triplicates for 5 days (mean BAFF secretion, RTX: 33.6 ± 6.2 pg/ml; ITP: 7.2 ± 1.2 pg/ml; HD: 20.2 ± 1 pg/ml). (C) CCL2 concentration in spleen supernatants after 5-day culture. CCL2 concentration was estimated as part of a multiplex 27-cytokine assay in spleen supernatants of 10^6 cells cultured in triplicate for 5 days (mean CCL2 secretion, RTX: 11,410 ± 228 pg/ml; ITP: 11,410 ± 1,236 pg/ml; HD: 3,233 ± 1,927 pg/ml). (D) Number of basophils in ITP and rituximab spleens. Spleen basophils were estimated by flow cytometry as numbers of HLA-DR–CD123–FcyRI+ cells per 10^6 cells (mean basophil numbers, RTX: 1,162 ± 79.8; ITP: 591 ± 178.4; HD: 201 ± 64.5). (E) ASC survival from HD spleens after culture with or without BAFF (100 ng/ml). Survival was estimated as in A. The values obtained with or without BAFF for each sample are connected by a straight line (median fold increased survival with BAFF: 8.3 [3.2–23]). Significant differences estimated by Mann-Whitney and paired t test (**P < 0.01, *P < 0.05). Symbols indicate individual samples; horizontal bars represent mean values (± SEM).

Main differences in cytokine secretion concerned IL-6 and BAFF, whose secretion was increased in ITP and rituximab-treated spleen supernatants, respectively. The increase in BAFF secretion could be a direct consequence of B cell depletion (44, 45) and might constitute a key factor, allowing, together with other players, for the settlement of long-lived PC in the rituximab-treated spleen. As recently highlighted, inflammatory B cells producing cytokines such as IL-6 may promote this local B cell activation, but the mechanism of tolerance breakdown remains unknown (46). Finally, a straight forward proposition coming out of these results is that ITP may be caused either by autoimmune CD20+ memory B cells and the short-lived PB and PC they produce (response to rituximab) or by long-lived CD20+ pathogenic PC present in the spleen (response to splenectomy after rituximab failure) or in other lymphoid niches (47) (failure of both treatments). One future therapeutic goal in ITP could be, according to our results, to modulate the splenic microenvironment, such as with an anti-BAFF therapy associated with rituximab, in order to prevent the generation of splenic long-lived PC.

**Methods**

**Patients with ITP and healthy controls**

Patients with ITP. All patients included fulfilled the following criteria: age, ≥18 years; ITP diagnosis according to the American Society Hematology guidelines. Exclusion criteria were as follows: other disease(s) associated with ITP (immunodeficiency, hepatitis C virus infection, lymphoproliferative disorders, thyroid or liver disease, and definite systemic lupus erythematosus [≥4 American Rheumatism Association criteria]). Evan’s syndrome has also been excluded. Response rate to splenectomy was defined according to the international criteria: complete response (defined as a platelet count >100 × 10^9/l); primary platelet response (defined as a platelet count ≥50 × 10^9/l), with at least the doubling of the baseline value without any rescue intervention during the preceding 8 weeks); and no response (defined as a platelet count <50 × 10^9/l). Blood samples were obtained for 4 RTX-treated patients at the time of splenectomy.

Controls. The characteristics of the subjects, including age and sex, at the time of sample collection, are detailed in Supplemental Table 2. All died from stroke. None presented with lymphoma or known autoimmune disease.

**Confocal microscopy analysis of human spleens**

Immediately after splenectomy, pieces of splenic tissue were excised and embedded in OCT (Sakura), snap frozen in liquid nitrogen, and stored at −80°C. Cryosections (7–9 μm) were cut, fixed in cold (−20°C) acetone for 10 minutes, rehydrated in wash buffer (TBS, pH 7.6), and incubated in blocking buffer (0.5% BSA and 10% goat serum in PBS) for 30 minutes at room temperature. Sections were then incubated for 60 minutes at room temperature, with the indicated primary antibodies in the blocking buffer solution (see Supplemental Table 3 for a complete list of antibodies). Incubations without primary antibodies were used as control. Sections were washed 3–4 times and incubated with the secondary antibody as indicated (30 minutes at room temperature). Sections were then washed and mounted in Fluoromont-G (Southern Biotech). Images were acquired by confocal microscopy with a LSM 700 (Zeiss). Fluorescence of single channels was measured, and control reference was systematically done. Pictures were taken with an objective ×40. Images were analyzed and processed with ImageJ version 1.46.

**Flow cytometry and cell sorting**

Antibodies used are listed in Supplemental Table 3. Intracellular staining was performed after cell fixation and permeabilization with the BD Cyto-
fix/Cytoperm solution. Stained populations were analyzed on a FACS-CantoII apparatus with the DIVA or FlowJo software. Cell sorting was performed with a FACSria cell sorter (Becton Dickinson), and gates were set to collect the CD19+CD20+CD27+CD38HLA-DR+ (PC) and HLA-DRhi (PB) fractions in HDs and patients with ITP and CD3+CD19+CD27+CD38hi cell fractions in patients treated with anti-CD20. The cell purity after sorting was greater than 99%.

**ELISPOT assays**

Anti-GplbIIa IgG PC detection. Multiscreen 96-well filter plates (MSIPS4510; Millipore) were coated by incubation overnight at 4°C with 2.5 μg/ml keyhole limpet hemocyanin (KLH), 10 μg/ml goat anti-human Ig polyvalent antibody (Invitrogen), or 30 μg/ml purified GplbIIa (Kordia Science) and coated in PBS/CaCl2 0.05%. 1 × 10⁶ cells were serially diluted in culture medium in triplicate before transfer to ELISPOT plates and cultured 4–6 hours in complete culture medium at 37°C under an atmosphere containing 5% CO₂. The ELISPOT was revealed with biotinylated goat anti-human IgG Fc (Invitrogen), followed by HRP-conjugated avidin (Vector Laboratories) and developed using 3-amino-9-ethylcarbazole (Sigma-Aldrich). Spots were counted in wells showing more than 3 specific spots in an ELISPOT reader with the AID software (version 3.5; Autoimmun Diagnostika). When detected, IgG-secreting anti-GplbIIa spot numbers were reported to IgG-positive spots. When no specific spot was detectable, a value “less than x” was assigned, with x corresponding to the frequency obtained if 1 GplbIIa spot were detected at the lowest dilution.

**Chemotaxis assay**

Culture supernatants of 1 × 10⁶ spleen cells per ml plated in 24-well plates were collected at day 5. Quantitative determination of secreted cytokines was performed with the Bio-Rad human cytokine 27-plex assay, carried out according to the manufacturer’s instructions. The human TNFSF13B/BAFF, CXCL12 (Quantikine, RD systems), and APRIL (USCNK) immunoassays were carried out according to the manufacturer’s instructions.

**Cytokine assays**

Culture supernatants of 1 × 10⁶ spleen cells per ml plated in 24-well plates were collected at day 5. Quantitative determination of secreted cytokines was performed with the Bio-Rad human cytokine 27-plex assay, carried out according to the manufacturer’s instructions. The human TNFSF13B/BAFF, CXCL12 (Quantikine, RD systems), and APRIL (USCNK) immunoassays were carried out according to the manufacturer’s instructions.

**Gene expression profiling**

RNA was isolated from sort-purified PC (CD19+CD20+CD27+CD38HLA-DR+) and PB (CD19+CD20+CD27+CD38HLA-DRhi) from 3 spleens of HDs and of patients with ITP (ITP1, ITP2, ITP3). PC (CD3+CD19+CD27+CD38hi) were isolated from 4 spleens of rituximab-treated patients (RTX1, RTX2, RTX6, RTX8). Total RNA was isolated using the RNeasy Micro Kit (QIAGEN). RNA quality and concentration were assessed using RNA 6000 Pico LabChips with a 2100 Bioanalyzer (Agilent Technologies). Total RNA (10 ng) was preamplified by Ribo-SPRIA (Ribo–single primer isothermal amplification) RNA Amplification using the Ovation Pico WTA Kit (NuGEN Technologies), fragmented, and labeled with biotin using the Encore Biotin Module (NuGEN Technologies), as recommended by the manufacturer. Expression analysis was performed using GeneChip Human U133 Plus 2.0 Arrays (Affymetrix). Gene expression levels were calculated using GCRMA, and flags were computed using Mass within R. To limit potentially biased measurements (background or saturating), all probes whose flags were absent or marginal were flagged as 0, whereas those present were flagged as 1. The group comparisons were done using a Student’s t test. To estimate the false discovery rate, we filtered the resulting P values at 0.05 (or 0.01 in certain cases) and considered data with 2- or 4-fold changes between samples. Data were subsequently compared to the gene ontology database (http://www.geneontology.org/). Complete data sets have been deposited in EMBL-EBI database (http://www.ebi.ac.uk/arrayexpress/, accession no. E-MEXP-3711).

**Statistics**

Statistical comparisons were made with the nonparametric Mann-Whitney test, and the Wilcoxon signed-rank test was used for paired samples using GraphPad Prism. A P value of ≤ 0.05 was considered as significant.

**Study approval**

The study was approved by the Agence de la Biomédecine and the Comité de Protection des Personnes (CPP) Ile de France-II for controls and by the CPP Ile de France-IX for patients with ITP. This study was conducted in accordance with the Helsinki Declaration, with informed consent obtained from each patient with ITP for collecting splenic samples.

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