Ofatumumab Is More Efficient than Rituximab in Lysing B Chronic Lymphocytic Leukemia Cells in Whole Blood and in Combination with Chemotherapy

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Ofatumumab (OFA) is a human anti-CD20 Ab approved for treatment of fludarabine-refractory B chronic lymphocytic leukemia (B-CLL). The efficacy of different immunotherapeutic strategies is best investigated in conditions that are as physiologic as possible. We have therefore compared the activity OFA and rituximab (RTX), alone or in combination with chemotherapeutic agents in unmanipulated whole blood assays, using flow cytometry. OFA (10–100 μg/ml) lysed B-CLL targets in whole blood more efficiently and with faster kinetics than RTX, with a mean 56% lysis at 24 h compared with 16%. This activity of OFA was fully complement dependent, as shown by >99% inhibition by anti-C5 Ab eculizumab and a lack of NK cell activation in whole blood. OFA-mediated NK cell activation was blocked by complement. OFA-mediated lysis could be increased an additional 15% by blocking CD55 and CD59 complement inhibitors. Interestingly, OFA-mediated lysis correlated significantly with CD20 expression levels (r² = 0.79). OFA showed overlapping dose response curves similar to those for RTX in phagocytosis assays using either human macrophages or neutrophils. However, phagocytosis was inhibited in the presence of serum or whole blood. Finally, combined treatment with mafosfamide and fludarabine showed that these therapeutic drugs are synergistic in B-CLL whole blood assays and show superior activity when combined with OFA compared with RTX. These results confirm in B-CLL samples and in physiologic conditions the superior complement mediated cytotoxicity induced by OFA alone compared with RTX, the lack of NK cell activation, and phagocytosis in these conditions and suggest effective chemioimmunotherapy strategies using this new generation anti-CD20 Ab. The Journal of Immunology, 2013, 190: 231–239.

The chimeric anti-CD20 mAb rituximab (RTX, MabThera) represents the gold standard for the treatment of B non-Hodgkin lymphoma (B-NHL) and other B cell neoplasias, when used in combination with chemotherapy in cyclophosphamide or fludarabine containing regimens. As a single agent, however, RTX has shown limited efficacy, especially in B chronic lymphocytic leukemia (B-CLL) and mantle cell lymphoma (MCL) (1–3). In B-CLL, RTX has therapeutic activity at the higher dose levels, but there is still need to substantially improve its activity (4).

The mechanisms of action of RTX in man include complement-mediated cytotoxicity (CDC), Ab-dependent cytotoxicity (ADCC), and phagocytosis (5). Several factors have been reported to influence its activity in vivo: high tumor burdens, FcγRs polymorphisms, CD20 expression levels, modulation of CD20 expression, and complement deficiency or consumption (6–9). The knowledge about translation of preclinical findings into the clinic is, however, still incomplete, and the most important mechanisms of action of in vivo in man in different clinical contexts are still controversial, despite a number of studies performed in vitro with a variety of isolated effector and target cells and several mouse models investigated.

To further improve the therapeutic efficacy of RTX, several new or modified anti-CD20 MAbs have been developed. In comparison with RTX, these MAbs are humanized or fully human and selected for either increased or decreased complement activation capacity, ADCC, or proapoptotic property. Ofatumumab (OFA; Arzerra) is a type I, fully human Ig (IgG1k) Ab. It binds to a different epitope of the CD20 cell surface Ag, closer to the cell membrane, redistributes CD20 into lipid rafts, binds more avidly to C1q (the first component of the complement cascade), and has a slower off-rate compared with RTX (10–12). These properties are thought to be the basis for the more efficient complement activation induced by OFA after binding to a variety of target cells, including primary B-CLL cells, which express low CD20 levels and resist RTX-mediated CDC (8, 11, 13). Besides activating complement efficiently, OFA has been shown to mediate ADCC by NK cells (10, 14). Little is known about other possible mechanisms, such as phagocytosis by macrophages and polymorphonuclear cells (PMNs).

OFA is currently under evaluation in phase II–III clinical trials in B-NHL and B-CLL, as a single agent or in combination with chemotherapy (http://www.clinicaltrials.gov) (15–18). Overall response rates as a single agent in relapsed or refractory B-CLL are 44–58% and 73–77% in previously untreated B-CLL (17–19), which compares favorably with the response previously observed for this subgroup of patients subjected to RTX monotherapy (20).
Furthermore, overall response to OFA is ~43% in B-CLL patients relapsed or refractory to RTX treatment (18). These data suggest an improved clinical activity of OFA in B-CLL with respect to the gold standard anti-CD20 Ab RTX. This higher activity may be due to its higher capacity to activate complement, particularly with neoplastic cells like B-CLL, which express low levels of CD20 (13), but this still remains to be demonstrated.

To compare the activity of OFA to that of RTX and identify the major mechanisms of action of this Ab in experimental conditions as physiologic as possible, we have investigated the activity of these anti-CD20 mAbs in unmanipulated B-CLL whole blood samples drawn in lepirudin (21, 22). We show that OFA is indeed more effective than RTX through a fully complement-mediated mechanism and that it can cooperate with standard chemotherapeutic agents such as fludarabine and mafosfamide.

Materials and Methods

Cells and Abs

Peripheral blood was drawn in lepirudin (Refudan; Celgene, Summit, NJ) at 50 μg/ml final concentration. Blood was obtained from patients with B-CLL/MCL, either at diagnosis or before any treatment, or from normal donors after informed consent. All patients were diagnosed by routine immunophenotypic, morphologic, and clinical criteria. Double staining with CD19 and slgK or slgM was performed to establish monoclonality and determine the percentage of neoplastic versus normal B cells present in the samples (<4% normal B cells with respect to neoplastic ones). In some cases, the mononuclear cell (MNC) fraction was also purified by standard Ficoll Hypaque gradient centrifugation (Seromed, Berlin, Germany).

MNCs were then cultured in RPMI 1640 medium supplemented with 10% FBS, 2 μM glutamine (all from Euroclone, Milano Italy), and 110 μM gentamicin (PHT Pharma, Milan, Italy). The study was approved by the hospital ethics committee.

RTX (MabThera), chimeric IgG1 was obtained from Roche Italia (Monza, Italy); OFA (Arzerra, human IgG1k) was a gift from Glaxo Smith Kline (Verona, Italy). Control Ab trastuzumab (TRX; Herceptin, human-IgG1k) was a gift from Dr. C. Klein (Roche Glycart, Berlin, Germany). The lowest phase was collected, and sedimentation over a 4% dextran solution for 30 min was performed. The upper phase contained ~90% CD15+ PMNs. Thawed B-CLL cells were stained with 0.1 μM CFSE (Molecular Probes) and then plated on the macrophages at a 1:1 ratio, in the presence or absence of therapeutic Abs. In some cases, whole blood from healthy donors was added. The plates were incubated at 37°C for 2 h, harvested, washed, stained with CD19-Cy7 (BD Biosciences), and analyzed with a flow cytometer (BD FACSCanto II, BD Biosciences). Whole blood samples were lysed and washed prior to FACS analysis. Phagocytosing cells were defined as PKH26/CFSCE/CD19APC−.

PMNs were purified from peripheral blood of normal donors by layering them on standard Ficoll Hypaque gradient centrifugation (Seromed, Berlin, Germany). The lowest phase was collected, and sedimentation over a 4% dextran solution for 30 min was performed. The upper phase contained ~90% CD15+ PMNs. Thawed B-CLL cells were stained with 2 μM PKH26 and mixed with purified PMNs or whole blood in a 5:1 ratio (B-CLL:PMN), in presence or absence of Abs. In some experiments with purified PMNs, 20% HS or heat-inactivated HS was added. Cells were incubated at 37°C for 2–24 h, and then stained with anti-CD15–FITC and CD19-Cy7 (BD Biosciences), washed, and analyzed with a flow cytometer (BD FACSCanto II, BD Biosciences). Percentage phagocytosis was defined as the percentage of PKH26+/CD15+/CD19− cells relative to total CD15+ cells. In some cases, samples were centrifuged onto glass slides at 500 rpm for 5 min using a Shandon centrifuge. Slides were dried, fixed in 2% paraformaldehyde, and stained with 1.5 μg/ml DAPI in mounting medium (Vectashield; Vector Laboratories, Burlingame, CA). Slides were viewed with a Nikon Eclipse E800 microscope using a Nikon 20X Plan Fluor DICM lens. At least four representative fields were photographed. The total number of PMNs (PKH26+/CD15+/CD19−) and the percentage of phagocytic PMN (PKH26+/CD15+/CD19−) were counted in a double-blind fashion using the Image J program (National Institutes of Health).

Treatment with OFA combined with chemotherapy

Unmanipulated peripheral blood (400 μl) of B-CLL/B-NHL patients in 50 μg/ml lepirudin (21) was plated in the presence or absence of different concentrations of RTX, OFA, or control irrelevant Ab TRX. In some cases, 200 μg/ml blocking anti-C5 mAb eculizumab (Soliris, Alexion Pharmaceuticals, Cheshire, CT), 10 μg/ml of functionally blocking anti-CD55 (BRIC216; International Blood Group Reference Laboratory [IBGRL], Bristol, U.K.) or anti-CD59 (BRIC229; IBGRL) Abs, or control irrelevant Ab was added 5 min before the lytic Abs. Whole blood samples were incubated for 2–24 h at 37°C, 5% CO2, and then stained for 15 min at room temperature with allophycocyanin-Cy7-conjugated anti–CD-45, FITC-conjugated anti-CD19 Ab and PerCP-7AAD (BD Biosciences), as described previously (22). After incubation, samples were lysed with hypotonic lysis solution (Pharm Lyse; BD Biosciences) to eliminate platelets and RBCs. Samples were then analyzed by double fluorescence on a FACSCanto II instrument (BD Biosciences). Cell death was measured as a decrease in CD19+/7AAD− population in treated versus control samples after gating on the CD45+ population.

Measurement of NK cell activation

MNCs or whole blood in lepirudin from patients or normal donors were incubated for 2 h at 37°C with 5% CO2 with different concentrations of OFA, RTX, and GA101 as positive control (22) or TRX as negative control. Cells were then incubated with anti-CD56-Cy7 and anti-CD107a–PE conjugated Abs, washed in PBS and, in the case of whole blood, red cells were lysed in hypotonic lysis solution as above and analyzed using a FACSCanto II Instrument (BD Biosciences). Cells were gated on the mononuclear population and percentage CD107a in the CD56− fraction was then measured. Double staining of the control samples with anti-CD56-Cy7 and anti-CD16–FITC demonstrated in all cases that more than 95% of CD56+ cells were CD16− NK cells.

Phagocytosis assay

In vitro differentiated macrophages were obtained from purified CD14+ monocytes cultured in the presence of 20 ng/ml recombinant human MCSF (R&D Systems) for 5–7 d, as described previously (23). The cells were then stained with 2 μM PKH26 (Sigma-Aldrich), washed, and incubated in culture medium overnight. Thawed B-CLL cells were stained with 0.1 μM CFSE (Molecular Probes) and then plated on the macrophages at a 1:1 ratio, in the presence or absence of therapeutic Abs. In some cases, whole blood from healthy donors was added. The plates were incubated at 37°C for 2 h, harvested, washed, stained with CD19-Cy7 (BD Biosciences), and analyzed with a flow cytometer (BD FACSCanto II, BD Biosciences). Whole blood samples were lysed and washed prior to FACS analysis. Phagocytosing cells were defined as PKH26/CFSCE/CD19APC−.

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Statistical analysis

The data were analyzed using paired or unpaired Student t tests, as appropriate. The p values are *p < 0.05, **p < 0.01, and ***p ≤ 0.001.

Results

OFA lyses B-CLL cells in whole blood in a fully complement-dependent manner in lepirudin drawn blood

To investigate the activity of OFA in physiologic conditions, we created an assay in unmanipulated whole blood. For this purpose, we searched for an anticoagulant that would not interfere with any
of the known immune-mediated or direct effects of therapeutic MAbs and tested in particular sodium citrate and leprirudin (21). We observed that neither sodium citrate nor leprirudin inhibited the deposition of complement fragments C3 and C9 onto the target cell membrane (Fig. 1A) or CDC (Fig. 1B). In contrast, citrate significantly inhibited CD107a induction, a marker for NK degranulation (Fig. 1C), as well as ADCC itself (Fig. 1D), whereas lepirudin had no effect on these mechanisms (Fig. 1C, 1D). Similarly, phagocytosis by macrophages was decreased by citrate, although not significantly, but was unaltered in the presence of leprirudin (Fig. 1E). Finally, citrate or leprirudin had no effect on the homotypic adhesion induced by the type II anti-CD20 MAb GA101 (Fig. 1F). We therefore chose leprirudin for all subsequent studies, because this anti-coagulant does not interfere with any of the biologic effects of therapeutic Abs tested in vitro.

To further define our experimental conditions with our test Ab OFA, we performed a dose-response curve using purified B-CLL cells and 20% HS. As shown in Fig. 2A, OFA had little activity at 1 \( \mu \)g/ml, but reached \( \sim \)54.7% lysis at 10 \( \mu \)g/ml and \( \sim \)70% at 100 \( \mu \)g/ml. The highest concentration of 500 \( \mu \)g/ml did not significantly increase lysis, suggesting that a plateau is reached at 100 \( \mu \)g/ml; therefore, this high dose was not used in further experiments.

We next used B-CLL whole blood samples drawn in leprirudin to investigate the cytotoxic activity of OFA in more physiologic conditions. Samples were incubated with 1, 10, or 100 \( \mu \)g/ml OFA for 4 or 24 h. As shown in Fig. 2B, OFA-mediated cell lysis was maximal already at 4 h, reaching \( \sim \)55% at 100 \( \mu \)g/ml (\( n = 4 \)). The dose response curve in whole blood was similar to that observed with purified B-CLL in the presence of 20% HS, with significantly higher lysis observed at 100 \( \mu \)g/ml OFA compared with 10 \( \mu \)g/ml (\( p < 0.01 \); Fig. 2B). The lowest dose (1 \( \mu \)g/ml) also had little activity in whole blood. The relatively high dose of mAb required suggested that the major mechanism of OFA in whole blood is CDC. Indeed, this could be demonstrated by the addition of 200 \( \mu \)g/ml anti-C5 MAb eculizumab to the reaction (22, 24), which completely abolished OFA-mediated lysis of B-CLL cells in whole blood, at both 4 and 24 h (Fig. 2C).

To investigate directly whether ADCC might also have a role in the mechanism of action of OFA in whole blood, we measured induction of CD107a at 2 h as a surrogate marker of ADCC (25). We had shown previously that GA101, a defucosylated anti-CD20 Ab, can indeed induce ADCC and NK cell degranulation even in presence of HS or in whole blood (22). We therefore used the GA101 Ab as positive control in these experiments. Using three different B-CLL whole blood samples, we observed limited CD107a in-
duction in presence of optimal concentrations of either OFA or RTX (1 or 10 mg/ml), which reached ∼4% in both cases, but was not statistically significant (Fig. 2D). In contrast, degranulation of NK cells in whole blood reached 16.4% and 21.1%, with GA101 at 1 and 10 mg/ml, respectively (Fig. 2D; p < 0.001). Lack of CD107a induction by OFA in whole blood was presumably due to inhibition of CD16 binding by the Ab following complement deposition onto the Ab, as already described for RTX (26). Indeed, we could show that CD107a expression induced on purified NK cells by either RTX or OFA was inhibited by addition of 20% HS, but not heat-inactivated HS. In contrast CD107a induction by GA101 was not inhibited (Supplemental Fig. 1). These data confirm the role of complement in inhibiting NK cell activation by either RTX or OFA.

We conclude that OFA, like RTX, does not efficiently activate NK cell degranulation and ADCC in whole blood, in contrast to the defucosylated Ab GA101. Furthermore, these data confirm that the major mechanism of action of OFA in whole blood is complement-mediated lysis.

**Lysis of B-CLL in whole blood is more efficient with OFA than with RTX but still depends on CD20 expression levels**

It is well known that the relatively low level of CD20 expressed by B-CLL is one important factor of resistance of these cells to RTX treatment, in vitro and in vivo. We therefore compared the activity of OFA or RTX in whole blood and investigated the role of CD20 levels in this lysis. Thirteen untreated B-CLL/MCL whole blood samples were drawn in lepirudin, and increasing concentrations of Abs were added. Lysis was measured at both 4 and 24 h. OFA at 10 and 100 μg/ml showed superior activity compared with RTX at 4 h (data not shown) and 24 h (Fig. 3A). Lysis was 10.5% and 16% with RTX at 24 h and 40% and 56% with OFA at 10 and 100 μg/ml, respectively (p < 0.001). OFA was therefore ∼3.5–4 fold superior versus RTX at these concentrations (Fig. 3A); 100 μg/ml OFA was again more effective than 10 μg/ml of the same Ab (p < 0.01, Fig. 3A). We noted, however, that lysis with OFA was highly variable between samples, ranging from 15–99% at 100 μg/ml Ab (Fig. 3B), which could depend on CD20 expression levels. Indeed, as shown in Fig. 3C, lysis induced by either OFA or RTX correlated directly with the number of CD20 expressed on the cells, except that the level of lysis was in all cases superior with OFA compared with RTX. More in detail, OFA induced measurable CDC lysis (12–35%) even in the presence of B-CLL targets expressing ≤5000 CD20 molecules per cell. Lysis was higher (59–79%), with expression between 5000 and 10,000 molecules/cell; finally, it was highly efficient (>90%), with CD20 expression of 15,000 and greater. In contrast, RTX-mediated lysis was low (generally <10%) at <10,000 CD20 molecules/cell and reached only 35–50% in cases expressing at least 15,000 CD20 molecules/cell (Fig. 3C).

Given the dependence of both OFA and RTX on CD20 expression levels and the fact that these Abs bind to different CD20 epitopes, we investigated whether these Abs could show increased efficacy when combined. We could not, however, observe any additive or synergistic effects of the anti-CD20 when combined compared with the single mAbs (data not shown).

We conclude that OFA-mediated lysis in whole blood is more efficient than that of RTX, but it is still dependent on CD20 expression levels. Furthermore, OFA and RTX do not synergize in these conditions.

**OFA-mediated lysis can be enhanced by blocking anti-CD55 or anti-CD59**

Because OFA does not induce 100% lysis of B-CLL cells, even after 24 h, we searched for means of increasing this activity. Functional blocking of complement inhibitor proteins CD55 and CD59 levels have an important role in regulating complement-dependent cytotoxicity and can enhance RTX-mediated cytotox-
We therefore investigated whether this was also true for OFA in whole blood. Blocking anti-CD55 and CD59 mAbs (10 μg/ml), alone or in combination, were added to OFA in B-CLL whole blood and lysis measured at 4 and 24 h. Blocking anti-CD55 and anti-CD59 alone at both 4 and 24 h induced a 10% and 7% increase in OFA-mediated lysis, respectively, but this was not statistically significant. In contrast, in the presence of both blocking Abs, B cell lysis increased from 36 to 56% at 4 h and from 54 to 77% at 24 h, with a net increase of 20% and 23% at 4 and 24 h, respectively (*p*, 0.01). Control Ab TRX had no effect (Fig. 3D). These data show that although OFA is more effective than RTX at activating complement, this activity is still partially held in check by membrane complement inhibitors CD55 and CD59 in whole blood.

Both OFA and RTX induce phagocytosis by macrophages and neutrophils, but this is inhibited in whole blood

To investigate other possible mechanisms of action of OFA that might occur in vivo, we compared the activity of RTX and OFA in phagocytosis assays using in vitro differentiated macrophages and purified B-CLL cells as targets. As shown in Fig. 4A, RTX and OFA showed overlapping dose-response curves in standard phagocytosis assays in culture medium, suggesting similar efficacy of the two mAbs through this mechanism. Because we have shown previously that excess Igs or whole blood strongly inhibit phagocytosis, we also analyzed phagocytosis in the presence of whole blood. Whole blood inhibited phagocytosis by ~90%, whether RTX or OFA were used (Fig. 4B; *p* < 0.001). We conclude that macrophage-mediated phagocytosis is not significantly different in the presence of OFA compared with RTX and that both are inhibited in whole blood.

Polymorphonuclear neutrophils (PMN) are a major blood component that can mediate phagocytosis of Ab-opsonized targets, although this has been seldom investigated with anti-cancer Abs. We therefore determined whether phagocytosis by PMN could take place in whole blood. We observed that PMN did not mediate significant phagocytosis of labeled B-CLL targets in whole blood.
blood (Fig. 6A), whereas the same purified PMN used in parallel at the same effector:target ratio were active (Fig. 5A). This finding suggested that phagocytosis by PMN may be inhibited by complement activation. Indeed we could show that the addition of 20% serum, but not heat-inactivated serum, inhibited phagocytosis mediated by purified PMN and either RTX or OFA (Fig. 6B; \( p < 0.01 \)). The same experiment was also repeated with 50% fresh or heat-inactivated HS, a concentration that is more similar to that present in whole blood. As expected, the addition of 50% HS, like 20% HS, strongly inhibited phagocytosis (\( p < 0.01 \)). Interestingly, 50% heat-inactivated serum also inhibited phagocytosis, although to a lower extent than untreated 50% HS (Fig. 6C). These data suggest that in whole blood, phagocytosis may be inhibited by both complement activation and the excess IgG present in plasma.

We conclude that purified neutrophils can phagocytose opsonized B-CLL targets in the presence of either OFA or RTX, but that this mechanism is not significant in whole blood because inhibition by complement and excess IgG.

**OFA in combination with mafosfamide and fludarabine**

Unconjugated therapeutic mAbs are best combined with chemotherapeutic agents for optimal activity in vivo, and the development of methods that allow the rapid identification of the best combinations is warranted. In this context, we have analyzed both in whole blood assays and using purified mononuclear cells from B-CLL patients receiving the combination of OFA or RTX with fludarabine or mafosfamide (or both), two drugs commonly used in B-CLL (28–30). The exposure of CLL cells for 28 h to the combination of fludarabine and mafosfamide at 1 \( \mu \)g/ml resulted in...
the expected synergistic cytotoxicity compared with either drug alone (Fig. 7A, 7B). Using isolated B-CLL, either drug induced ~10% cytotoxicity and >40% when combined (Fig. 7A, bar 9 compared with 3 and 6). Similarly, using B-CLL whole blood samples (Fig. 7B), the cytotoxicity of the compounds combined (38%, bar 9) was significantly more than the sum of the cytotoxicities of each compound (~25% adding bars 3 and 6). As expected, OFA alone at 10 μg/ml was more cytotoxic than RTX when using either MNC (in presence of HS) or whole blood from B-CLL patients, with 20–25% mean lysis with OFA against less than 5% with RTX (Fig. 7A and B, bars 1 and 2). Lysis by OFA was approximately additive over that observed with fludarabine or mafosfamide alone or both compounds together (bars 5 versus 3, 8 versus 6, and 11 versus 9), so that maximal lysis with both chemotherapeutic agents plus OFA reached 53–56% with either MNC or whole blood (Fig. 7A, 7B, bar 11). The combination of the three drugs was stronger using OFA than RTX by ~15%, reflecting the greater complement-mediated cytotoxicity of OFA compared with RTX (Fig. 7A, 7B, bars 5, 8, and 11 compared with bars 4, 7, and 10).

We conclude that OFA can be combined with fludarabine and mafosfamide and has an additive effect with respect to these compounds, which is stronger than that observed with RTX. Synergistic and additive effects can be observed using both purified MNCs in the presence of HS or whole blood from B-CLL patients, suggesting that the whole blood assay can be a rapid in vitro assay to test the activity of different immunotherapeutic strategies.

Discussion
In this report, we have compared the activity of new and old generation anti-CD20 Abs OFA and RTX in whole blood assays, which are likely to better represent the in vivo condition in the circulation. Furthermore, we have investigated the mechanism of action of OFA, showing that complement is the major mechanism of OFA in these conditions. Finally, we have measured the efficacy of the Abs in combination with chemotherapeutic agents, showing that OFA in whole blood has an additive effect over fludarabine- and mafosfamide-mediated cytotoxicity.

Lysis of B-CLL targets by OFA alone required at least 10 μg/ml Abs and was maximal at 100 μg/ml. Lysis was variable, ranging from 15% to >99% (mean 55%) at 100 μg/ml. Lysis by OFA was more rapid and 3–6-fold higher than that observed with the same doses of RTX (range, 0–58% lysis; mean, 14% at 100 μg/ml). Furthermore, we could demonstrate in the whole blood assays that lysis by OFA was fully complement dependent, because it was completely inhibited by excess blocking anti-CS Ab eculizumab. The higher CDC activity of OFA compared with RTX is expected because the Ab was selected for its high complement-activating capacity, and this property has already been demonstrated using cell lines or purified B-CLL cells as targets (10–13, 31, 32). However, this mechanism had not been characterized previously in unmanipulated whole blood (i.e., in the presence of all blood components, platelets, RBCs, granulocytes, plasma, all of which express soluble or membrane bound complement inhibitors that could affect the ultimate outcome) and at cell concentrations that reflect the in vivo conditions. Several detailed studies have shown that the major reasons for higher CDC by OFA in regard to RTX are its high-aavidity binding to C1q, the first complement component, its recognition of a CD20 epitope close to the plasma membrane, and its slower off-rate in regard to RTX (10–12, 31, 33).

Interestingly, the efficacy of B-CLL–MCL lysis by OFA correlated significantly with the CD20 expression levels on the target, similar to that observed with RTX in vitro and in vivo (8, 34) and with OFA using purified neoplastic targets (32). However, OFA-mediated lysis was in all cases higher than that observed with RTX. We could confirm significant CDC even of low CD20 expressing B-CLL by OFA, in contrast to virtually no lysis of these targets by RTX. This finding is in agreement with previous data showing that RTX-resistant cells may be sensitive to OFA (13, 31). Furthermore, we could show that neoplastic samples expressing intermediate to high CD20 showed relatively high lysis ranging from 50–99%. Nonetheless, membrane-bound complement inhibitor was holding the complement cascade in check, even in the presence of OFA, because lysis in whole blood could be increased by an additional 15% in the presence of blocking anti-CD59 and anti-CD55 Abs. This finding indicates that strategies to block complement inhibitors simultaneously to OFA, as previously suggested also for RTX, could further improve the anti-CD20 Ab activity in vivo (32, 35).

In our whole blood assays, we could also show that OFA does not induce significant NK cells activation, seen as CD107a induction (<5%), in contrast to the defucosylated GA101 Ab, which activated up to 25% of NK cells. Lack of NK cell activation parallels what has been observed with RTX and is likely due to inhibition of FcyRIIIA binding by complement fragments deposited onto the cell-bound Ab (26, 36). This result supports a fully complement dependent mechanism of target cell killing in whole blood. Whether NK cell activations takes place in tissues where complement levels may be lower is unclear and should be investigated further.

We also investigated whether OFA mediated phagocytosis by in vitro differentiated macrophages or by neutrophils. Phagocytosis by macrophages showed overlapping dose-response curves with OFA and RTX using purified B-CLL as targets. The uptake of targets by macrophages was likely true phagocytosis, and not the previously described trogocytosis (37), because our assay used a triple fluorescence method, which detects targets effectively
enlarged by effector cells. As expected in whole blood, macrophage phagocytosis was not significant because of IgG or complement competition, or both, as demonstrated previously for RTX (22, 38). Similarly, PMNs were able to phagocytose both RTX or OFA opsonized targets with similar dose-response curves, although this mechanism was relatively slow, being maximal at 24 h and at relatively high Ab concentrations (10 μg/ml). To our knowledge, the PMN-mediated phagocytosis of anti-CD20 opsonized targets has not been demonstrated previously. Interestingly, PMN-mediated phagocytosis was inhibited by serum complement and in part by excess IgG, and it was undetectable in whole blood. Therefore, the lack of PMN-mediated phagocytosis in whole blood is likely due to inhibition of CD16B binding by complement fragments deposited onto the anti-CD20 Ab, as shown previously for CD16A on NK cells, as well as to competition between IgG complexes in serum and opsonized targets for binding to this same FcγR. We could show that CD16B is required for phagocytosis by PMN (L. Bologna and F. Da Roit, unpublished observations and manuscript in preparation). We conclude that phagocytosis by PMNs is unlikely to be a significant mechanism of action of OFA or RTX in the circulation, in agreement with the fully complement dependent lysis observed in whole blood, as discussed above. Whether this mechanism takes place in tumor tissues remains to be determined.

Analysis of the effect of OFA with fludarabine and mafosfamide showed the expected synergism between these two standard chemotherapy agents in whole blood, previously demonstrated with purified cells, and a clear additive effect of OFA at 10 μg/ml, which added ∼25% lysis, that is more than that obtained with RTX (5% increased lysis). Therefore, the combination of OFA with chemotherapeutics may effectively achieve a high level of target lysis with relatively low doses of drugs, perhaps diminishing the toxicity and the complement consumption observed at high doses of Abs (39). We believe that our whole blood system may be a useful screening assay in physiologic conditions for the best combinations of unconjugated Abs with chemotherapeutic agents. Furthermore, other biological effects of Abs could also be investigated in the same conditions in the future, such as the potentially complement components or loss of CD20, as suggested by the effect of high-burden disease (6, 34). Nonetheless, high dosing confirms in physiologic conditions that relatively high doses of Abs (39) may achieve the best circulating B cell depletion (14). Our data show that the standard RTX dose (375 mg/m²). This dose is in part based on previous I–II studies with OFA in B-CLL. These studies use high OFA doses, generally 2000 mg/infusion, I–II studies with OFA in B-CLL. These studies use high OFA concentrations in plasma of at least 100 μg/ml). This finding is particularly true considering the sink requirements for sustained in vivo activity of a therapeutic human anti-CD20 antibody.

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Disclosures
The authors have no financial conflicts of interest.

References
1. Cheson, B. D., and J. P. Leonard. 2008. Monoclonal antibody therapy for B-cell non-Hodgkin’s lymphoma. N. Engl. J. Med. 359: 613–626.
2. Lin, T. S., M. S. Lucas, and J. C. Byrd. 2003. Rituximab in B-cell chronic lymphocytic leukemia. Semin. Oncol. 30: 483–492.
3. Huhn, D., C. von Schilling, M. Wilhelm, A. D. Ho, M. Hallek, R. Kuse, W. Knauf, U. Riedel, A. Hinke, S. Strock, et al; German Chronic Lymphocytic Leukemia Study Group. 2001. Rituximab therapy of patients with B-cell chronic lymphocytic leukemia. Blood 98: 1326–1331.
4. O’Brien, S. M., H. Kantarjian, D. A. Thomas, F. J. Giles, J. E. Freireich, J. Cortes, S. Lerner, and N. A. Storb. 2001. Rituximab dose-escalation trial in chronic lymphocytic leukemia. J. Clin. Oncol. 19: 2165–2170.
5. Taylor, R. P., and M. A. Lindorfer. 2008. Immunotherapeutic mechanisms of anti-CD20 monoclonal antibodies. Curr. Opin. Immunol. 20: 444–449.
6. Bernstein-Lazo, C. A., G. Deeb, A. White, I. Benece-Bruckler, D. Maloney, M. Crazzuman, D. Green, J. Rosenberg, P. McLaughlin, and D. Shen. 1998. Association of serum Rituximab (IDEC-C2B8) concentration and anti-tumor response in the treatment of recurrent low-grade or follicular non-Hodgkin lymphoma. Ann. Oncol. 9: 995–1001.
7. Cartron, G., L. Dacheux, G. Salles, P. Solal-Celigny, P. Bards, P. Colombat, and H. Watier. 2002. Therapeutic activity of humanized anti-CD20 monoclonal antibody and polymorphism in IgG Fe receptor FcgammaRIIa gene. Blood 99: 954–958.
8. Golay, J., M. Lazzari, V. Fachinetti, S. Bernasconi, G. Borleri, T. Barbui, A. Rambaldi, and M. Intronza. 2001. CD20 levels determine the in vitro susceptibility to rituximab and complement of B-cell chronic lymphocytic leukemia: further regularity by CD55 and CD59. Blood 96: 3383–3389.
9. Kennedy, A. D., P. V. Beam, M. D. Solga, D. J. Dilloo, M. A. Lindorfer, C. E. Hess, J. J. Densmore, M. E. Williams, and R. P. Taylor. 2004. Rituximab infusion promotes rapid complement depletion and acute CD20 loss in chronic lymphocytic leukemia. J. Immunol. 172: 3280–3288.
10. Teeling, J. L., R. R. French, M. S. Cragg, J. van den Brakel, S. Pleyter, H. Huang, C. Chan, P. W. Parren, C. E. Hack, M. Dechant, et al. 2004. Characterization of new human CD20 monoclonal antibodies with potent cytolytic activity against non-Hodgkin lymphomas. Blood 104: 1793–1800.
11. Teeling, J. L., W. J. Maciek, J. P. Waegeman, J. van den Brakel, S. A. Beers, R. R. French, T. van Meerten, S. Ebeling, T. Vink, W. J. Soolstraat, et al. 2006. The biological activity of human CD20 monoclonal antibodies is linked to unique epitopes on CD20. J. Immunol. 177: 362–371.
12. Pawluczukowycz, A. W., F. J. Beurek, P. V. Beam, M. A. Lindorfer, J. G. van den Winkel, P. W. Parren, and R. P. Taylor. 2009. Binding of submaximal C1q promotes complement-dependent cytotoxicity (CDC) of B cells opsonized with anti-CD20 mAbs ofatumumab (OFA) or rituximab (RTX): considerably higher levels of CDC are induced by OFA than by RTX. J. Immunol. 183: 749–758.
13. Barth, M. J., F. J. Hernandez-Ilizaritzu, C. Mavis, P. C. Tsai, J. F. Gibbs, G. Deeb, and M. S. Crazzuman. 2012. Ofatumumab demonstrates activity against rituximab-sensitive and -resistant cell lines, lymphoma xenografts and primary tumour cells from patients with B-cell lymphoma. Br. J. Haematol. 156: 490–498.
14. Bleeker, W. K., M. E. Munk, W. J. Mackus, J. H. van den Brakel, S. A. Beers, M. J. Glennie, J. G. van den Winkel, and P. W. Parren. 2008. Estimation of dose requirements for sustained in vivo activity of a therapeutic human anti-CD20 antibody. Br. J. Haematol. 140: 303–312.
15. Crazzuman, M. S., L. Fayad, V. Delwail, G. Cartron, E. Jacobsen, K. Kaluczkowycz, B. K. Link, P. Futter-Brown, J. Radford, A. Hellmann, et al; 405 Study Investigators. 2012. Ofatumumab monotherapy in rituximab-refractory follicular lymphoma: results from a multicenter study. Blood 119: 3698–3704.
16. Crazzuman, M. S., G. Hess, O. V. Gadeberg, L. M. Pedersen, N. Goldstein, I. Gupta, R. C. Jewell, T. S. Lin, S. Libsy, and G. Deeb, et al; 409 Study Investigators. 2012. Chemoinmunotherapy with ofatumumab in combination with CHOP in previously untreated follicular lymphoma. Br. J. Haematol. 157: 438–445.
17. Wierda, W. G., T. J. Kipps, J. Mayer, S. Stilgenbauer, C. D. Williams, A. Hellmann, T. Robak, R. R. Furman, P. Hillmen, M. Trneny, et al; Hx-CD20-406 Study Investigators. 2010. Ofatumumab as single-agent CD20 immunotherapy in fludarabine-refractory chronic lymphocytic leukemia. J. Clin. Oncol. 28: 1749–1755.
18. Wierda, W. G., S. Padmanabhan, G. W. Chan, I. V. Gupta, S. Libsy, and A. Osterborg; Hx-CD20-406 Study Investigators. 2011. Ofatumumab is active in patients with fludarabine-refractory CLL irrespective of prior rituximab: results from the phase 2 international study. Blood 118: 5126–5129.
19. Coullier, B., S. Lepretre, L. M. Pedersen, O. Gadeberg, H. Fredriksen, M. H. van Oers, J. Wooldridge, J. Kloczko, J. Holowiecki, A. Hellmann, et al. 2008. Safety
and efficacy of ofatumumab, a fully human monoclonal anti-CD20 antibody, in patients with relapsed or refractory B-cell chronic lymphocytic leukemia: a phase 1-2 study. *Blood* 111: 1094–1100.

20. Mavromatis, B. and B. D. Cheson. 2003. Monoclonal antibody therapy of chronic lymphocytic leukemia. *J. Clin. Oncol.* 21: 1874–1881.

21. Mollnes, T. E., O. L. Brekke, M. Fung, H. Fure, D. Christiansen, G. Bergseth, V. Videm, K. T. Lappegård, J. Köhl, and J. D. Lambris. 2002. Essential role of the C5a receptor in *E. coli*-induced oxidative burst and phagocytosis revealed by a novel lepirudin-based human whole blood model of inflammation. *Blood* 100: 1869–1877.

22. Bologna, L., E. Gotti, M. Manganini, A. Rambaldi, T. Intermesoli, M. Introna, and J. Golay. 2011. Mechanism of action of type II, glycoengineered, anti-CD20 monoclonal antibody GA101 in B-chronic lymphocytic leukemia whole blood assays in comparison with rituximab and alemtuzumab. *J. Immunol.* 186: 3762–3769.

23. Leidi, M., E. Gotti, L. Bologna, E. Miranda, M. Rimoldi, A. Sica, M. Roncalli, G. A. Palumbo, M. Introna, and J. Golay. 2009. M2 macrophages phagocytose rituximab-opsonized leukemic targets more efficiently than m1 cells in vitro. *J. Immunol.* 182: 4415–4422.

24. Wang, Y. 2006. Complementary therapies for inflammation. *Nat. Biotechnol.* 24: 1224–1226.

25. Alter, G., J. M. Malenfant, and M. Altfeld. 2004. CD107a as a functional marker of the natural killer cell activity. *J. Immunol. Methods* 294: 15–22.

26. Wang, S. Y., E. Racila, R. P. Taylor, and G. J. Weiner. 2008. NK-cell activation and antibody-dependent cellular cytotoxicity induced by rituximab-coated target cells is inhibited by the C3b component of complement. *Blood* 111: 1456–1463.

27. Golay, J., L. Zaffaroni, T. Vaccari, M. Lazzari, G. M. Borleri, S. Bernasconi, F. Tedesco, A. Rambaldi, and M. Introna. 2000. Biologic response of B lymphoma cells to anti-CD20 monoclonal antibody rituximab in vitro: CD55 and CD59 regulate complement-mediated cell lysis. *Blood* 95: 3900–3908.

28. Keating, M. J., S. O’Brien, M. Albizar, S. Lerner, W. Plunkett, F. Giles, M. Andreff, J. Cortes, S. Faderl, D. Thomas, et al. 2005. Early results of a chemoimmunotherapy regimen of fludarabine, cyclophosphamide, and rituximab as initial therapy for chronic lymphocytic leukemia. *J. Clin. Oncol.* 23: 4079–4088.

29. Wierda, W. G., T. J. Kipps, and M. J. Keating. 2005. Novel immune-based treatment strategies for chronic lymphocytic leukemia. *J. Clin. Oncol.* 23: 6325–6332.

30. Schulz, H., S. K. Klein, U. Rehwald, M. Reiser, A. Hinke, W. U. Knauf, W. E. Aulitsky, M. Hensel, M. Herold, D. Huhn, et al; German CLL Study Group. 2002. Phase 2 study of a combined immunochemotherapy using rituximab and fludarabine in patients with chronic lymphocytic leukemia. *Blood* 100: 3115–3120.

31. van Meerten, T., H. Rozemuller, S. Hol, P. Moerter, M. Zwart, A. Hagenbeek, W. J. Mackus, P. W. Parren, J. G. van de Winkel, S. B. Ebeling, and A. C. Martens. 2010. HuMab-708, a monoclonal antibody directed against the membrane-proximal small loop epitope of CD20 can effectively eliminate CD20 low expressing tumor cells that resist rituximab-mediated lysis. *Haematologica* 95: 2063–2071.

32. Ge, X., L. Wu, W. Hu, S. Fernandez, C. Wang, X. Li, J. R. Brown, and X. Qin. 2011. rILYd4, a human CD59 inhibitor, enhances complement-dependent cytotoxicity of ofatumumab against rituximab-resistant B-cell lymphoma cells and chronic lymphocytic leukemia. *Clin. Cancer Res.* 17: 6702–6711.

33. Du, J., H. Yang, Y. Guo, and J. Ding. 2009. Structure of the Fab fragment of therapeutic antibody Ofatumumab provides insights into the recognition mechanism with CD20. *Mol. Immunol.* 46: 2419–2423.

34. Cartron, G., R. U. Trappe, P. Solal-Célligny, and M. Hallek. 2011. Interindividual variability of response to rituximab: from biological origins to individualized therapies. *Clin. Cancer Res.* 17: 19–30.

35. Macor, P. C., Tripodo, S. Zorzet, E. Piovan, F. Bossi, R. Marzari, A. Armadori, and F. Tedesco. 2007. In vivo targeting of human neutralizing antibodies against CD55 and CD59 to lymphoma cells increases the antitumor activity of rituximab. *Cancer Res.* 67: 10556–10563.

36. Wang, S. Y., S. Veeramani, E. Racila, J. Cagley, D. C. Fritzinger, C. W. Vogel, W. St. John, and G. J. Weiner. 2009. Depletion of the C3 component of complement enhances the ability of rituximab-coated target cells to activate human NK cells and improves the efficacy of monoclonal antibody therapy in an in vivo model. *Blood* 114: 5322–5330.

37. Daubeuf, S., M. A. Lindorfer, R. P. Taylor, E. Joly, and D. Hadrisser. 2010. The direction of plasma membrane exchange between lymphocytes and accessory cells by trogocytosis is influenced by the nature of the accessory cell. *J. Immunol.* 184: 1987–1998.

38. Lefebvre, M. L., S. W. Krause, M. Salcedo, and A. Nardin. 1997. 2006. Ex vivo-activated human macrophages kill chronic lymphocytic leukemia cells in the presence of rituximab: mechanism of antibody-dependent cellular cytotoxicity and impact of human serum. *J. Immunother.* 29: 388–397.

39. Beurskens, F. J., M. A. Lindorfer, M. Farooqui, P. V. Beum, P. Engelberts, W. J. Mackus, P. W. Parren, A. Wiestner, and R. P. Taylor. 2012. Exhaustion of cytotoxic effector systems may limit monoclonal antibody-based immunotherapy in cancer patients. *Clin. Cancer Res.* 18: 95: 3900–3908.

40. Byrd, J. C., T. Murphy, R. S. Howard, M. S. Lucas, A. Goodrich, K. Park, M. Pearson, J. K. Waselesko, G. Ling, M. R. Grever, et al. 2001. Rituximab using a thrice weekly dosing schedule in B-cell chronic lymphocytic leukemia and small lymphocytic lymphoma demonstrates clinical activity and acceptable toxicity. *J. Clin. Oncol.* 19: 2153–2164.