Enhancement of the Antibody-Dependent Cellular Cytotoxicity of Low-Fucose IgG1 Is Independent of FcγRIIIa Functional Polymorphism

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ABSTRACT

Purpose: The most common polymorphic variant of Fcγ receptor type IIIa (FcγRIIIa), FcγRIIIa-158F, has been associated with inferior clinical responses to anti-CD20 chimeric IgG1 rituximab compared with FcγRIIIa-158V. As we previously found that removal of fucose residues from the oligosaccharides of human IgG1 results in enhanced antibody-dependent cellular cytotoxicity, we compared the effects of the FcγRIIIa gene (FCGR3A) polymorphism on normal and low-fucose versions of rituximab on antibody-dependent cellular cytotoxicity.

Experimental Design: The polymorphism at position 158 of FcγRIIIa was determined for the peripheral blood mononuclear cells (PBMCs) of 20 healthy donors. The PBMCs were then used as effector cells to compare the antibody-dependent cellular cytotoxicity of rituximab and a low-fucose version, KM3065. The contributions of the different cell types within the PBMC to antibody-dependent cellular cytotoxicity were examined.

Results: We found KM3065-mediated antibody-dependent cellular cytotoxicity was increased 10 to 100-fold compared with rituximab for each of the 20 donors. In contrast to rituximab, KM3065 antibody-dependent cellular cytotoxicity enhancement was similar for both FCGR3A alleles and thus independent of genotype. In addition, antibody-dependent cellular cytotoxicity of both KM3065 and rituximab requires natural killer cells but not monocytes or polymorphonuclear cells. The antibody-dependent cellular cytotoxicity (ADCC) of each of the 20 donors correlated with the natural killer cell numbers present in the PBMCs. Importantly, using KM3065, the ADCC mediated by effector cells bearing the lower affinity variant FcγRIIIa-158F was significantly increased compared with rituximab-mediated ADCC using effector cells bearing the higher affinity FcγRIIIa-158V receptors.

Conclusions: The use of low-fucose antibodies might improve the therapeutic effects of anti-CD20 therapy for all patients independent of FcγRIIIa phenotype beyond that currently seen with even the most responsive patients.

INTRODUCTION

Rituximab is a chimeric human IgG1 antibody targeting the B-cell–specific antigen CD20 and is widely used for the treatment of non-Hodgkin’s lymphoma (1–4). Several in vivo and clinical studies indicate that antibody-dependent cellular cytotoxicity (ADCC) is an essential therapeutic mechanism of rituximab. However ADCC-mediated effects are suboptimal for the majority of patients receiving the current drug due to a polymorphic variation of antibody binding receptors (5–8).

ADCC, a lytic attack on antibody-targeted cells, is triggered after binding of lymphocyte receptors (FcRs) to the antibody Fc region. ADCC activity is dependent on the structure of complex-type oligosaccharides linked to CH2 domain of the antibody. The content of galactose (9, 10), bisecting-GlcNAc (11, 12), and fucose (13, 14) in the antibody oligosaccharide have each been reported to effect ADCC. In a previous study, we demonstrated that fucose is the most critical antibody oligosaccharide component, and the reduction of fucose content in rituximab oligosaccharides results in >100-fold enhancement of ADCC activity (14). Moreover, we recently demonstrated that the low-fucose version of anti-CC chemokine receptor 4 chimeric IgG1 has enhanced ADCC, which results in more potent in vivo antitumor activity than the conventional high-fucose IgG1 (15), demonstrating reduction of the fucose content of human IgG1-type antibody, a powerful modification for the improvement of effector function.

Most therapeutic antibodies, including rituximab, are produced by Chinese hamster ovary (CHO) cells because of the ability of these cells to maintain protein productivity in cultures of high cell mass grown in well-defined media. CHO cells express high level of α1,6-fucosyltransferase, which catalyzes the fucosylation of complex oligosaccharides (14), and as a consequence, CHO-produced antibodies most often have oligosaccharides with a high fucose content. Antibodies with reduced fucose can be produced by altering the host cells from CHO cells to other cell lines with reduced fucosylation activity such as rat YB2/0 cells (14) or the CHO variant cell line, Lec13 (13).

Although the detailed mechanism by which the reduction of fucose enhances ADCC is not fully understood, Shields et al. (13) have demonstrated both low-fucose anti-HER2 and anti-EGF IgG1 had significantly increased binding to FcγRIIIa on natural killer (NK) cells, the predominant subtype of FcγRs
capable of mediating ADCC. More recently, Okazaki et al. (16) showed, using thermodynamic and kinetic measurements, that reducing the fucose content of IgG1 enhances the binding enthalpy and association rate for IgG1-FcγRIIIa binding. However, whether other effector cell populations in addition to NK cells contribute to the enhanced ADCC of low-fucose antibody remains unknown.

FcγRIIIa gene (FCGR3A) allelic polymorphism generates receptors containing either a phenylalanine (F) or a valine (V) at amino acid position 158. This variation results in human IgG1 binding with higher affinity to NK cells of homozygous FCGR3A-158V (V/V) donors than those of homozygous FCGR3A-158F (F/F) donors, and this appears to activate NK cells more effectively (17, 18). Although FcγRIIIa binding affinity is presumed to be correlated with enhanced ADCC activity, there have been no quantitative investigations with effector cells from multiple donors into the relationship between FCGR3A polymorphism and actual ADCC value.

Importantly, several reports have recently suggested that the FCGR3A genotype is associated with the clinical efficacy of rituximab with the clinical response of patients bearing FcγRIIIa-158F being significantly inferior to the patients with the FcγRIIIa-158V receptors (6–8). Although rituximab has other potential effector functions, these reports underscore the importance of ADCC in clinical outcomes. However, these studies did not directly address the mechanism of the difference between the phenotypes, nor provide any potential mechanisms to overcome the resistance.

We have previously developed a low-fucose variant of rituximab designated KM3065 (14). In the present study, we measured rituximab- and KM3065-mediated ADCC using peripheral blood mononuclear cells (PBMCs) as effector cells from multiple healthy donors whose genotype at position 158 was determined to clarify the relationships between the enhanced ADCC by low-fucose IgG1 and FCGR3A genotype.

MATERIALS AND METHODS

Anti-CD20 Chimeric IgG1s. Rituximab, mouse-human chimeric IgG1-type anti-CD20 antibody, was purchased from Genentech, Inc. (San Francisco, CA). KM3065, low-fucose version of rituximab, was produced by rat myeloma YB2/0 cells (Genentech, Inc. San Francisco, CA), and their appropriate molecular weights confirmed previously (19). Plasmids were transfected into rat myeloma cell line YB2/0 by electroporation. Proteins were purified from culture supernatant by Ni-NTA chromatography (Qiagen, Valencia, CA), and their appropriate molecular weights confirmed by SDS-PAGE.

IgG1 Binding to Recombinant FcγRs. ELISA plates were coated with 5 μg/mL anti-Tetra His antibodies (Qiagen) in PBS. After blocking with PBS containing 1% BSA-PBS, purified receptors were incubated on the plates at room temperature for 2 hours. After washing with PBS containing 0.05% Tween 20 (wash buffer), serial dilutions of polymeric IgG in 1% BSA-PBS were incubated at room temperature for 2 hours. Polymeric IgG1s were prepared in 1% BSA-PBS by mixing equimolar amounts of each IgG1 and anti-F(ab’2)2 antibody (Jackson ImmunoResearch, West Grove, PA) at room temperature for 1 hour. After washing with the wash buffer, bound IgG1s were detected using peroxidase-labeled goat antihuman IgG (H+L) antibodies (American Qualex, San Clemente, CA), with 2, 2-azinobis (3-ethylbenzthiazoline-6-sulfonic acid) as the substrate. The reaction was stopped with 5% SDS, and absorbance at 415 nm was measured on an Emax plate reader (Molecular Devices, Menlo Park, CA). For FcγRIIIa, the study was also conducted as described above with monomeric IgG.
**FCGR3A-158F/V Genotyping.** Genotyping of the FCGR3A-158V/F polymorphism was performed by using a PCR-based allele-specific restriction analysis assay with genomic DNA prepared from aliquots of peripheral blood as described previously (17).

**Quantitation of Effector Cell Proportions in PBMCs.** Quantitation of the NK cells and monocytes in PBMCs were determined by flow cytometric analysis as follows: PBMCs (1 x 10^6) were incubated on ice for 30 minutes with either FITC-labeled anti-CD3 antibody and phycoerythrin-labeled anti-CD56 antibody (Beckman Coulter, Tokyo, Japan) for NK cell quantitation, or phycoerythrin-labeled anti-CD14 antibody for monocyte quantitation in the presence of 3.8 mg/mL human IgG (Welfide, Osaka, Japan) as blocking reagent. After incubation, cells were washed twice with PBS and analyzed using an EPICS XL-MCL flow cytometer (Beckman Coulter). The CD56^+CD3^- cells and CD14^- cells were defined as NK cells or monocytes, respectively.

**RESULTS**

**Effector Cell Analysis and FcγR Binding Profiles of Rituximab and Its Low-Fucose Version, KM3065.** Rituximab and its low-fucose version KM3065 are composed of identical amino acid sequences and thus exhibit indistinguishable CD20 binding activity (14). They vary only the amount of N-linked oligosaccharides without fucose, which is 6% for rituximab and 91% for KM3065. This results in KM3065 exhibiting much higher ADCC than rituximab (14). To identify the effector cell populations contributing to ADCC of rituximab and its low-fucose counterpart, we used various cell fraction to measure the ADCC of each of the anti-CD20 IgGs against CD20^-^ B-cell lymphoma Raji cells. We compared total PBMCs, purified NK cells, PMNs, or monocytes as effector cells, all of which could potentially mediate ADCC via FcγR signaling. The effector cell populations were prepared from the same donor; however, the FCGR3A polymorphism at position 158 was not determined.

As shown in Fig. 1A, KM3065 showed >100-fold higher ADCC than rituximab when total PBMCs were used as effector cells. A similar increase of ADCC was found with KM3065 only when NK cells were used as effector cells. In contrast, neither monocytes nor PMNs demonstrated measurable ADCC activity in this assay. These results demonstrate that the ADCC of both low-fucose and conventional high-fucose IgG1 is primarily mediated by NK cells in which the predominant IgG binding receptor is FcγRIIIa.

We next investigated the ELISA binding profiles of anti-CD20 IgGs to FcγRs of the various subtypes to better understand the mechanism responsible for increased ADCC of KM3065 mediated by the NK cells. There was no significant difference in the binding of rituximab or KM3065 to FcγRI (Fig. 1B). KM3065 showed a slight increase in binding compared with rituximab for FcγRIIa and FcγRIlb. In contrast, the binding of KM3065 was greatly increased with equivalent binding at ~100-fold less protein to either FcγRIIIa-158F or FcγRIIIa-158V when compared with rituximab. These data are

![Fig. 1](https://clincancerres.aacrjournals.org/content/20/21/6250/F1.large.jpg)  
**Fig. 1** Effector analysis in ADCC and FcγR binding profiles of the two anti-CD20 IgGs. A, ADCC against Raji cells of the two anti-CD20 IgGs using different cell populations from the same donor as effector cells. The kind of effector cell population (underlined) and E/T ratio used are indicated in each panel. Each E/T ratio is roughly proportional to the contents of each effector cell populations in peripheral blood, except for the experiment with higher number of NK cells (E/T = 20). The incubation times during the assay were 4 hours, except for 16 hours for monocyte-mediated ADCC. The mean cytotoxicities (%) ± SD of triplicates are shown. Dashed lines represent antibody-independent cellular cytotoxicity (AICC), the cytotoxicity in the absence of antibody. B, binding profiles of the two anti-CD20 IgGs to various FcγRs. The mean values ± SD of triplicates are shown.
consistent with those previously reported for low-fucose versions of anti-HER2 IgG1 (13).

**FCGR3A-158F/V Genotyping of 20 PBMC Donors.**

We next studied the clinical implications of treating patients of different FCGR3A genotypes with low-fucose antibodies by determining the ADCC activity of low-fucose IgG1 using effector cells from donors for whom the FCGR3A genotypes had been determined. Hence, FcyRIIIa-158F/158V genotyping was conducted for 20 randomly selected healthy donors. As summarized in Table 1, the number of donors with F/F genotype was 15, and 4 donors had the V/F genotype and 1 donor had the V/V genotype. The allelic frequency calculated was 0.85 for FCGR3A-158F allele and 0.15 for FCGR3A-158V allele. The distribution observed was slightly but not significantly (\( P = 0.25, \chi^2 \) test) biased toward the FCGR3A-158F allele compared with that in previous reports of the Japanese population as a whole (allelic frequency of FCGR3A-158F was 0.72 to 0.74; refs. 20, 21).

**Comparison of Effect of FCGR3A Genotype on ADCC Exerted by Anti-CD20 Antibodies.**

We compared the ADCC of rituximab and KM3065 (1 to 100 ng/mL) using PBMCs from donor cells when rituximab was used. The improved potency of the low-fucose antibody KM3065 (F/F) (Fig. 3B) additionally demonstrates the high potency of the low-fucose antibody and the FCGR3A-158V genotype, with the following rank order of potency at each IgG1 concentrations: KM3065 (V carrier) > KM3065 (F/F) > rituximab (V carrier) > rituximab (F/F) (Fig. 4B).

**DISCUSSION**

Therapeutic antibodies have been postulated to have multiple effector mechanisms *in vivo* based on *in vitro* studies. For example, with rituximab, potent ADCC, potent complement-dependent cytotoxicity, and relatively weaker direct apoptosis induction have been observed *in vitro* (3). What is important in

The use of the KM3065 also reduced the difference in ADCC activity between the low-affinity and high-affinity Fc receptors. In contrast to V carriers showing a ~10-fold greater activity than F/F for rituximab, there was no significant difference for KM3065.

Importantly, the ADCC of KM3065 by the less potent F/F donor cells was significantly higher than the most responsive donor cells when rituximab was used.

**Correlation between ADCC and the Percentage of NK Cells or Monocytes in PBMCs.** To better understand the importance of the FcYRs and confirm the role of NK cells, we investigated the correlation between ADCC and the percentages of NK cells or monocytes, both of which express FcYRIIIa. The percentages of NK cells and monocytes in PBMCs of each donors determined by flow cytometry are summarized in Table 1. There was no significant correlation between FCGR3A genotype and the percentage of these two effector cells. As shown in Fig. 3, ADCC against Raji cells was shown to correlate significantly with the percentage of NK cells. In contrast, ADCC did not correlate with the percentage of monocytes. The NK cell dependence and monocyte independence of ADCC were similarly observed when WIL2-S cells were used as target cells (data not shown).

**NK-Mediated ADCC Normalized for Cell Number.**

As both FCGR3A genotype and percentage of NK cells in PBMCs were shown to affect ADCC of anti-CD20 IgG1s in this study, the ADCC values obtained above were then reanalyzed by normalizing to a fixed number of NK cells (10^6 cells). We considered that the ADCC normalized for NK cell number best describes the precise relationship between FCGR3A genotype and ADCC. ADCC 10^6 NK cells for individuals (Fig. 4A) or mean value of each genotypes (Fig. 4B) additionally demonstrates the high potency of the low-fucose antibody and the FCGR3A-158V genotype, with the following rank order of potency at each IgG1 concentrations: KM3065 (V carrier) > KM3065 (F/F) > rituximab (V carrier) > rituximab (F/F) (Fig. 4B).

**Table 1** Characterization of the donors

<table>
<thead>
<tr>
<th>Characterization of the donors</th>
<th>F/F</th>
<th>V/F</th>
<th>V/V</th>
<th>P*</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of donors</td>
<td>15</td>
<td>4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>NK cells,† %, median (range)</td>
<td>15.1 (8.73–28.5)</td>
<td>13.6 (8.55–22.8)</td>
<td>6.27</td>
<td>0.404</td>
</tr>
<tr>
<td>Monocytes,‡ %, median (range)</td>
<td>9.85 (5.15–20.1)</td>
<td>10.6 (4.18–11.2)</td>
<td>15.9</td>
<td>0.874</td>
</tr>
<tr>
<td>AICC (Raji),§ %, median (range)</td>
<td>3.51 (1.45–13.0)</td>
<td>3.67 (1.96–4.82)</td>
<td>0.448</td>
<td>0.211</td>
</tr>
<tr>
<td>AICC (WIL2-S),¶ %, median (range)</td>
<td>16.0 (13.6–30.3)</td>
<td>17.3 (14.5–22.7)</td>
<td>13.3</td>
<td>0.848</td>
</tr>
</tbody>
</table>

* Determined by unpaired Student’s *t* test between F/F versus V carriers (V/F + V/V).
† Percentage of NK cells in PBMCs.
‡ Percentage of monocytes in PBMCs.
§ Antibody-independent cellular cytotoxicity against Raji cells in 4-hour 51Cr release assay.
¶ Antibody-independent cellular cytotoxicity against WIL2-S cells in 4-hour 51Cr release assay.

Abbreviation: AICC, antibody-independent cellular cytotoxicity.
patients and, ultimately, which is critical for optimal clinical efficacy is less well understood. However, recent findings have demonstrated that ADCC plays a key role and suggests that improvements in ADCC will manifest improvements in clinical outcomes (6–8). A functional polymorphism of FCGR3A for patients receiving rituximab has been associated with inferior clinical responses. The polymorphic variant of FcγRIIIa for patients with inferior responses, FcγRIIIa-158F, shows a lower affinity for rituximab compared with the other variant FcγRIIIa-158V. FCGR3A-158F allele is more prevalent than FCGR3A-158V allele and the largest population, FCGR3A-158F/F, typically 40 to 50% in various ethnic groups (18, 20–23). Therefore, it is expected that the majority of patients would be less responsive to conventional antibody therapies that mediate ADCC. Hence, finding methods to improve the ADCC of antibodies for this major patient population is an important unmet clinical need.

As we have previously shown that low-fucose antibodies have augmented ADCC, we studied if these effects were seen in both patient populations with different Fc receptor genotypes and especially the resistant genotype. Our results clearly demonstrate that the enhanced ADCC mediated by the low-fucose anti-CD20 IgG1 is achieved independent of the FCGR3A genotypes; KM3065 showed greatly increased ADCC when compared with rituximab in all 20 donors. Importantly, KM3065 ADCC mediated by F/F donors with low-affinity receptors was

![Antibody-dependent cellular cytotoxicity (ADCC) of anti-CD20 IgG1s using PBMCs from 20 donors. A. ADCC of 20 donors according to the absence or presence of FCGR3A-158V allele (F/F and V carriers: top and bottom panels, respectively) in a 4-hour 51Cr-release assay in the presence of the anti-CD20 IgG1s (1, 10, and 100 ng/mL) at an E/T ratio of 20:1. Raji cells or WIL2-S cells were used as target cells (left and right panels, respectively). The mean value of duplicates are shown. The plots of the same donors were connected with lines. Statistically significant differences between rituximab- and KM3065-mediated ADCC are marked by *(P < 0.05), **(P < 0.01), or ****(P < 0.001) as determined by paired t test. B. mean ADCC of each FCGR3A genotype groups. Statistically significant differences between different genotype groups are marked by *(P < 0.05) or ***(P < 0.01) as determined by unpaired t test.
>10-fold higher than rituximab ADCC mediated by the most responsive donors with FcγRIIIa-158V receptors. This result implies that low-fucose IgG1 may overcome the reduced responsiveness to conventional IgG1 therapy of patient with low-affinity FcγRIIIa receptors and may have a improved therapeutic effect in all patients. Supporting this observation, the binding affinity of KM3065/FcγRIIIa-158F interaction was 3 to 4-fold higher than that of rituximab/FcγRIIIa-158V interaction, as we have demonstrated by calorimetric and kinetic methods very recently (16).

The study of different cell types that express Fcγ receptors demonstrated that ADCC was mediated via NK cells and not by monocytes or PMNs (Fig. 1A). Monocytes and PMNs are reported to effect ADCC when they are primed with cytokines (24–26), an aspect that remains to be examined. One possible reason for the observed inability of monocytes to exhibit ADCC in the current studies is the different glycosylation of FcγRIIIa receptors between leukocyte populations that result in a higher binding affinity for monomeric IgG on NK cells than on monocytes (27). PMNs express high levels of FcγRIIIb, the phosphotyrosylinositol-linked subtype of FcγRIII, which shares the highly homologous extracellular domain with FcγRIIIa. FcγRIIIb lacks a cytoplasmic tail and has not been demonstrated to have intrinsic signaling capacity. Although its biological role is poorly understood, it has been suggested that FcγRIIIb triggers intracellular signaling in cooperation with activation receptor FcγRIIa (28–30) or complement receptor CR3 (31). It has also been postulated that the capacity of PMNs to exert ADCC may depend on the intracellular structure of specific antigen molecules (32). The capability of low-fucose antibody to mediate ADCC by monocytes or PMNs merits additional investigated for other antigens than CD20.

In addition to FCGRA3 polymorphism, the proportion of FcγRIII-positive cells in PBMCs has been reported to be another factor that affects ADCC (33). In the present study, NK cells were the sole effector cells in anti-CD20 IgG-mediated ADCC (Fig. 1A), and this result was confirmed by the significant correlation of ADCC of the 20 donor PBMC and NK cell proportions (Fig. 3). Hence, we calculated the data on ADCC for a fixed number of NK cells to provide an index for ADCC normalizing individual differences in NK cell number to more accurately measure the ADCC for each FCGRA3 genotype. The plot of ADCC/10⁴ NK cells still showed the following hierarchy: KM3065 (V carrier) > KM3065 (F/F) > rituximab (V carrier) > rituximab (F/F). This indicates the advantage of low-fucose IgG1, irrespective of the FCGRA3 polymorphism, in the absence of heterogeneity in NK cell proportions among individuals.

There are three genotypes for FCGRA3 polymorphism (V/V, V/F, and F/F). Although the allelic frequency determined in this study does not significantly differ from previously published data, the number of FCGRA3-158V carriers (n = 5),
especially V/V donors (n = 1), were unexpectedly low. Consequently, additional studies with more donors will be required to elucidate whether V/V and V/F NK cells inherently differ on ADCC potential. With respect to clinical data, Anolik et al. (7) have reported a significant difference in efficacy of B-cell depletion between FCGR3A-158V carriers and FCGR3A-158F/F in the treatment of systemic lupus erythematosus with rituximab, although they did not state the differences between V/V and V/F. In contrast, reports of B lymphoma have shown that V/V patients were more responsive for rituximab therapy than F carriers (V/F and F/F), but these studies failed to detect the differences between V/F and F/F (6, 8). Given that the V/F effector cells would be expected to have an intermediate potential, it is possible that the difference in clinical response between the three genotypes could be obscured, for example, (a) by some individual factors other than FCGR3A polymorphism that affects ADCC such as heterogeneity in NK cell proportion, or (b) with rituximab, some other effector functions (complement-dependent cytotoxicity, or apoptosis induction), which can also function in vivo (3).

In conclusion, the data presented suggests a critical need for the clinical use of low-fucose IgG1 for therapeutic antibodies that mediate ADCC as a mechanism of action. This modification might improve the clinical outcomes of all patients independent of FCGR3A genotypes and, in particular, overcome the shortcomings of the therapy received by the majority of patients that have the low-affinity FcyRIIIa polymorphic version. Additional study will be necessary to examine the unde-
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