The Role of IgG Subclass in Antibody-Mediated Protection against Carbapenem-Resistant *Klebsiella pneumoniae*

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ABSTRACT Monoclonal antibodies (MAbs) have the potential to assist in the battle against multidrug-resistant bacteria such as carbapenem-resistant *Klebsiella pneumoniae* (CR-Kp). However, the characteristics by which these antibodies (Abs) function, such as the role of antibody subclass, must be determined before such modalities can be carried from the bench to the bedside. We performed a subclass switch on anticapsular monoclonal murine IgG3 (mIgG3) hybridomas and identified and purified a murine IgG1 (mIgG1) hybridoma line through sib selection. We then compared the ability of the mIgG1 and mIgG3 antibodies to control CR-Kp sequence type 258 (ST258) infection both in vitro and in vivo. We found by enzyme-limited immunosorbent assay (ELISA) and flow cytometry that mIgG3 has superior binding to the CR-Kp capsular polysaccharide (CPS) and superior agglutinating ability compared to mIgG1. The mIgG3 also, predictably, had better complement-mediated serum bactericidal activity than the mIgG1 and also promoted neutrophil-mediated killing at concentrations lower than that of the mIgG1. In contrast, the mIgG1 had marginally better activity in improving macrophage-mediated phagocytosis. Comparing their activities in a pulmonary infection model with wild-type as well as neutropenic mice, both antibodies reduced organ burden in a nonlethal challenge, regardless of neutrophil status, with mIgG1 having the highest overall burden reduction in both scenarios. However, at a lethal inoculum, both antibodies showed reduced efficacy in neutropenic mice, with mIgG3 retaining the most activity. These findings suggest the viability of monoclonal Ab adjunctive therapy in neutropenic patients that cannot mount their own immune response, while also providing some insight into the relative contributions of immune mediators in CR-Kp protection.

IMPORTANCE Carbapenem-resistant *Klebsiella pneumoniae* is an urgent public health threat that causes life-threatening infections in immunocompromised hosts. Its resistance to nearly all antibiotics necessitates novel strategies to treat it, including the use of monoclonal antibodies. Monoclonal antibodies are emerging as important adjuncts to traditional pharmaceuticals, and studying how they protect against specific bacteria such as *Klebsiella pneumoniae* is crucial to their development as effective therapies. Antibody subclass is often overlooked but is a major factor in how an antibody interacts with other mediators of immunity. This paper is the first to examine how the subclass of anti-capsular monoclonal antibodies can affect efficacy against CR-Kp. Additionally, this work sheds light on the viability of monoclonal antibody therapy in neutropenic patients, who are most vulnerable to CR-Kp infection.

KEYWORDS antibody therapy, monoclonal antibodies, isotype, carbapenem-resistant *Klebsiella pneumoniae*, antibiotic resistance, *Klebsiella*, antibody function

Monoclonal antibodies (MAbs) are becoming increasingly important in the treatment of a variety of different diseases, including infectious disease (1, 2). The escalating failure of traditional antibiotics to treat bacterial infections further empha-
sizes the importance of testing alternative therapies, including MAbs, against these pathogens (3). Much information regarding how antibody (Ab) structure influences interactions with pathogens remains to be discovered, and until recently the role of the Ab constant region and its different variants, or subclasses, had often been overlooked in therapeutic monoclonal Ab development. While four subclasses of IgG Abs exist in humans, the majority of MAbs used in the clinic are human IgG1 (hIgG1), the most prevalent subclass (4). The subclass of an Ab (dictated by the number of disulfide bonds joining the heavy chains), its fragment crystallizable (Fc) region, and other aspects of the heavy chain, affect what immune receptors and adaptors the antibody binds. Subsequently, these interactions determine the amplitude and character of the immune response (5). Some subclasses interact with more immunostimulatory Fc receptors on professional phagocytes, increasing their activity, while others bind to immunosuppressing receptors that act to reduce collateral damage caused by excessive inflammation (6). Additionally, subclasses can be responsible for differences in antigen binding, even when Abs have identical variable regions (7, 8). Understanding differences between IgG subclasses—how they bind, interact with the pathogen, and interact with other facets of immunity—is important to understanding which subclasses may provide a therapeutic benefit (8–12).

With the recent rise of multidrug-resistant Gram-negative bacteria, such as carbapenem-resistant Klebsiella pneumoniae (CR-Kp) (13), several laboratories have been focusing on developing antibodies against these pathogens (3, 14–17). These bacteria frequently infect immunocompromised populations that lack robust innate and adaptive immune responses (18, 19). Therefore, it is crucial to understand not only how different Ab subclasses act against these pathogens but also how they function in the context of immunocompromised states. We recently cloned murine IgG3 (mIgG3) monoclonal Abs that targeted the capsular polysaccharide (CPS) of wzi154 CR-Kp isolates, which fall within the clade 2 subfamily of the CR-Kp sequence type 258 (ST258) clonal group (14). Isolates of this conserved subgroup have been shown to be susceptible to Ab therapy through a variety of in vitro modalities such as killing by serum complement and action by neutrophils and macrophages, and such antibodies have been shown to be protective in vivo as well (14, 15, 20). We chose one of these, 17H12, to study the effects of switching IgG subclass on anti-Klebsiella Ab functionality. We report findings that the parent mlgG3 was superior to the new murine IgG1 (mlgG1) variant in binding ability, initiation of complement-mediated bactericidal activity by serum, and activation of neutrophil-mediated killing at lower antibody concentrations. Conversely, the new mlgG1 variant slightly outperformed the mlgG3 parent in promoting macrophage-mediated phagocytosis of the bacteria. Finally, our comparison within a pulmonary mouse challenge model shows comparable overall efficacy of both subclasses in reducing bacterial organ burden at both lethal and nonlethal inocula in wild-type mice. Interestingly, efficacy of both antibodies was maintained in neutropenic mice except at the lethal inoculum.

RESULTS

Parent 17H12 mlgG3 variant has superior binding of wzi154 capsular polysaccharide relative to that of the new subclass switch variant 17H12 mlgG1, despite identical variable regions. We first isolated a mlgG1 variant of the mlgG3 17H12 hybridoma line by using sib selection followed by fluorescence-activated cell sorting (FACS) and soft agar cloning, which we previously utilized (12). Although we sought to generate all three additional subclasses, only mlgG1 and mlgG2a variants were discovered in our initial screen, and only mlgG1 variants could be enriched by downstream sib selection. The mlgG1 hybridomas were verified to exclusively produce mlgG1, and the sequence of the variable region of the new clone was found to be identical to that of the mlgG3 parent (the characteristics of which have been previously published (14)).

To investigate how subclass switching affected binding, we compared the affinity of the new mlgG1 to that of its parent mlgG3 against the wzi154 CPS originally used to generate the MAb (14). Analysis by enzyme-limited immunosorbent assay (ELISA)
showed the mlgG1 to have 4-fold less binding than its mlgG3 counterpart, with 50% effective concentration (EC50) values of 27.6 nM (95% confidence interval [CI], 18.8 to 40.6 nM) and 6.81 nM (95% CI, 3.00 to 13.2 nM), respectively (Fig. 1A).

Next, we compared the ability of each Ab to agglutinate CR-Kp clinical isolates, utilizing flow cytometry to measure relative clump sizes by forward scatter (21). We began testing the Abs with the previously studied CR-Kp wzi154 strain 39 (MMC39) (14), which we transformed with a novel green fluorescent protein (GFP)-expressing plasmid, pProbe-KtBl. Using this transformant, referred to here as MMC39-GFP, we noted that mlgG3 promoted better agglutination than mlgG1; mlgG3-opsonized bacteria demonstrated higher forward scatter than mlgG1-opsonized bacteria at the same concentration of antibody and also achieved maximum forward scatter at lower concentrations of antibody (see Fig. S1 in the supplemental material). As 30 μg/ml provided the greatest disparity in agglutination between mlgG1 and mlgG3, we chose this antibody concentration and then compared relative agglutination across a number of CR-Kp isolates (Table 1). These isolates include those collected from Montefiore Medical Center (MMC) and Stony Brook University (SBU), including those previously studied (14, 22), as well as a previously studied isolate, 33576, from the mid-Atlantic states and its capsule-deficient variant (15) (Table 1). These strains cover the three most prevalent wzi subgroups within the ST258 clone (22–24). Measuring the percentage of aggregates larger than a baseline formed by control bacteria untreated with antibody (see Fig. S1 in the supplemental material), we found that both Abs improved agglutination of nearly all wzi154 strains relative to that promoted by a control mlgG1, but did not significantly promote agglutination of the capsule-deficient 33576 Δwzy strain or that of CR-Kp isolates of the wzi29 and wzi29 Δwzy subgroups (Fig. 1B, C).
Additionally, at this concentration the mIgG3 parent caused a higher percentage above baseline of agglutination than that caused by mIgG1 in 5 of 6 isolates. While the percent agglutination of strain 33576 did not significantly improve above baseline for either 17H12 mIgG1 or mIgG3, this was likely due to high observed baseline aggregation of the strain. In contrast, histograms of gated 33576 (and MMC5) demonstrate clear shifts in forward scatter between the mIgG3, mIgG1, and control groups, and aggregated raw mean forward scatter data show significantly higher agglutination by either Ab of all wzi154 bacteria relative to that in both controls (Fig. S1).

As previous studies have shown the importance of the Fc region in Ab binding to antigen, we performed F(ab')2 digests of both Abs to determine whether this may hold true for 17H12. We determined by ELISA that digestion of 17H12 mIgG3 led to a 2.7-fold loss of binding relative to whole mIgG3 (Fig. 1C). In contrast, digestion of 17H12 mIgG1 did not impact binding (Fig. S2).

Complement-dependent serum killing was exclusive to mIgG3. We next compared the ability of the two subclasses to mediate serum killing of CR-Kp. Using 20% fresh human serum, we determined that 17H12 mIgG3 caused 90.1% and 92.7% reductions in CFU of MMC39 CR-Kp after 60 and 120 min, respectively. In contrast, the mIgG1 caused 64.4% and 63.5% drops in CFU, respectively, similar to that caused by the control Ab (Fig. 2A). In strain 33576, 20% human serum was found to be insufficient to reduce CFU under any condition (Fig. 2B), but bacterial replication was inhibited by both subclasses, while bacteria exposed to the control multiplied 6-fold over 120 min. Increasing the percentage of serum to 40% improved CFU reduction of the 33576 strain, but in an antibody-independent manner (see Fig. S3 in the supplemental material). As previously described, the 33576 Δwzy strain exhibits pronounced sensitivity to serum in the absence of capsule (15), and nearly complete killing occurred irrespective of treatment (Fig. S3). Variability in killing was observed depending on the human serum donor, but effects were consistent between experiments using serum from the same donor. Additionally, heat inactivation (HI) of serum abrogated all killing effects against MMC39 and instead allowed *K. pneumoniae* growth, which both Abs partially limited (Fig. 2A).

We also specifically compared the relative amount of complement each antibody could fix. Using flow cytometry, we detected C3c and C5b-9 membrane attack complex deposition on MMC39, 33576, and 33576 Δwzy strains in the presence of either subclass (Fig. 2C and D, Fig. S3). We observed the parent mIgG3 to outperform the phosphate-buffered saline (PBS) control and the mIgG1, in deposition of C3c onto MMC39, but not onto 33576, which exhibited high background C3c deposition (Fig. 2C). With both strains, however, C5b-9 deposition was found to be increased when bacteria were preopsonized with mIgG3 (Fig. 2D). Controls confirmed that mIgG3 capsule binding caused deposition of serum-based complement, with incubation of the bacteria in 0% (Fig. 2C and D) or 20% HI serum resulting in no detectable deposition and the antibody failing to deposit additional complement onto the capsule-deficient 33576 Δwzy strain (Fig. S3).

Both subclasses improved macrophage-mediated phagocytosis, with mIgG1 performing marginally better than mIgG3. We next compared the ability of the subclasses to contribute to cell-mediated action against CR-Kp. Monocytes and mac-

**TABLE 1** List of CR-Kp strains used in the study

| Strain  | ST  | wzi | Source of isolate        | Reference |
|---------|-----|-----|--------------------------|-----------|
| MMC5    | 258 | 154 | Blood isolate from MMC   | 14        |
| MMC39   | 258 | 154 | Blood isolate from MMC   | 14        |
| MMC39-GFP | 258 | 154 | Transformant of MMC39    |           |
| SBU32   | 258 | 154 | Urine isolate from SBU   | 14        |
| SBU34   | 258 | 154 | Urine isolate from SBU   | 14        |
| 33576   | 258 | 154 | Isolate from mid-Atlantic| 20        |
| 33576 Δwzy | 258 | n/a | Isogenic mutant of 33576  | 15        |
| MMC36   | 258 | 29  | Blood isolate from MMC   | 14        |
| MMC38   | 258 | 50  | Blood isolate from MMC   | 14        |
FIG 2  Serum bactericidal effect and complement deposition mediated by 17H12 mIgG1 and mIgG3. (A and B) Growth curves of MMC39 (A) and 33576 (B) in 20% normal human serum (NHS) (both panels, solid lines) or in 20% heat-inactivated (HI)-NHS (panel A only, dashed lines) supplemented with 40 μg/ml of the indicated MAb. “100%” represents no increase in CFU from baseline. Error bars indicate standard error of the mean (SEM) of at least five independent experiments for MMC39 and three for strain 33576. Overall differences between treatment groups in the MMC39 (A) and in 33576 (B) strains were determined to be significant by repeated-measures two-way ANOVA (\( P = 0.002 \) and 0.0124, respectively) with results of individual comparisons at 60 min and 120 min using Tukey’s post hoc test displayed in the graph. (C and D) Fixation of complement components onto strains MMC39 and 33576, as measured by flow cytometry. Left histogram overlays depict representative data from three independent experiments, and right graphs show the means and SEM of the integrated geometric mean fluorescence intensity (igMFI) of each experiment. Histograms of treatments with serum are filled with solid colors, while those without serum have patterned fills. Overall differences between the variances of all treatments for each strain and each complement component were assessed for significance by repeated-measures one-way ANOVA (MMC39 C3c, \( P = 0.002; \) 33576 C3c \( P = 0.228; \) MMC39 C5-9 \( P = 0.013; \) 33576 C5-9 \( P = 0.020 \)) with results of Tukey’s post hoc test for multiple comparisons displayed in the graph. For all in-graph statistics, \( P \) values displayed in black are comparisons to the control IgG, whereas \( P \) values in red compare mIgG1 with mIgG3. \( P \) values are replaced with ns (not significant) if \( P > 0.1, \) \( * \) if \( P < 0.05, \) \( ** \) if \( P < 0.01, \) or \( *** \) if \( P < 0.001.\)
Phagocytes are important in CR-Kp clearance (25), and we have previously demonstrated 17H12 mlgG3 to enhance phagocytic uptake of numerous wzi154 CR-Kp strains (14). Therefore, we compared the ability of both variants to promote uptake using a CFU-based phagocytosis assay we previously performed (14, 26). Our data show mlgG1 to slightly improve J774A.1 macrophage phagocytosis of MMC39 relative to mlgG3, a trend that was also suggested in the phagocytosis of strain 33576 (Fig. 3A). In contrast, the 33576 Δwzy strain was phagocytosed irrespective of treatment condition. The difference in phagocytosis between mlgG1 and mlgG3 was subtle and was not evident when phagocytosis of MMC39-GFP was observed under fluorescence microscopy (Fig. 3B). Additionally, we found that uptake was not correlated with intracellular killing; after both J774A.1 macrophages and bone marrow-derived macrophages (BMDMs) had phagocytized the opsonized bacteria and external bacteria had been washed away, we observed by both CFU quantitation and by microscopy that the number of bacteria within these cells increased over time (data not shown). This observation suggests intracellular multiplication of CR-Kp after phagocytosis.

Neutrophil killing of CR-Kp improved with lower concentrations of mlgG3 than mlgG1. We next compared the ability of both antibodies to promote killing by neutrophils. Data in humans has shown that neutropenic patients may have reduced survival in cases of bacteremia caused by CR-Kp and other carbapenem-resistant Enterobacteriaceae (23). In mice, some studies have shown neutrophils to be important in CR-Kp clearance (15, 27), while others have shown them to be less valuable (25). Using a tube-based incubation assay with human neutrophils, we observed both antibodies to promote neutrophil-dependent killing of MMC39 in the presence of 5% autologous serum at 40 μg/ml (Fig. 3C). When we reduced the dose to 10 μg/ml, however, mlgG3 demonstrated improved efficacy, while mlgG1 lost all efficacy relative to that of the control. Antibody-mediated killing by neutrophils was dependent on serum, as coinubcation of neutrophils with HI serum failed to reduce bacterial CFU.

We then compared the ability of the two antibodies to promote neutrophil reactive oxygen species (ROS) production in response to CR-Kp. We used MMC39, MMCS, SBU32, and SBU34, and either 5% normal human serum (NHS) or 20% HI-fetal bovine serum (FBS) in reactions (Fig. 3D; see also Fig. S4 in the supplemental material). These data indicate that both mlgG1 and mlgG3 promoted ROS production to comparable degrees. However, strains had differing ability to induce ROS production, with strains SBU32 and SBU34 having high constitutive production of ROS in the absence of either monoclonal Ab, whereas base ROS in MMC39 and MMCS were nearly absent (Fig. 3D, Fig. 4). Furthermore, baseline ROS production in SBU32 and SBU34 occurred irrespective of whether NHS or HI-FBS was used, though NHS appeared to promote marginally higher production.

Both subclasses improved CR-Kp lung clearance in vivo, including within neutropenic mice. Finally, we compared the protective efficacy of the subclasses in vivo, using a pulmonary infection model we previously utilized in BALB/c mice (14). Because we observed these two MAbs to enhance neutrophil-mediated killing, we compared the relative abilities of the subclasses to control organ burden in both c57BL/6 wild-type mice and neutropenic mice, which were generated by Ly6G antibody-mediated depletion. After depleting neutrophils or administering a control Ab, we infected mice with a sublethal dose of MMC39 preopsonized with either the mlgG1, mlgG3, a control mlgG1, or Tris-glycine buffer alone. As we found no significant differences between the mlgG control and the Tris-glycine vehicle, these groups were combined for analysis. We first observed higher CFU lung burden in neutropenic mice, in contrast to observations in previous studies (25, 28). Additionally, we observed efficacy of both subclasses in reducing bacterial burden in the lung in both wild-type and neutropenic mice, with 17H12 mlgG3 having a small but significant advantage over the mlgG3 (Fig. 4A). Additionally, the mlgG1 appeared to promote higher expression of the inflammatory cytokines gamma interferon (IFN-γ), tumor necrosis factor alpha (TNF-α), interleukin-12 (IL-12), and IL-17 in neutropenic mice, suggesting higher im-
FIG 3 Comparison of cell-mediated phagocytosis and killing. (A) Phagocytosis of the MMC39, 33576, and 33576 Δwzy strains by J774A.1 murine macrophage-like cells after incubation with 40 μg/ml of respective antibody. The phagocytic index is calculated as the number of CFU recovered from the plate, divided by the number of cells plated. Bars depict means and SEMs of three independent experiments, with wells performed in triplicate. Overall differences in the variance of all treatments for each strain were assessed for significance by repeated-measures one-way ANOVA (MMC39 $P < 0.001$; 33576 $P = 0.221$; 33576 Δwzy $P = 0.520$), with results of Tukey’s post hoc test for multiple comparisons displayed in the graph. (B) Representative images of antibody-mediated phagocytosis of MMC39-green fluorescent protein (GFP) by J774A.1 macrophages. Images were taken at ×40 magnification with an EVOS microscope using brightfield and GFP channels. (C) Killing of preopsonized MMC39 by human neutrophils after 60 min. Bars depict mean and SEM of three independent experiments. Within the results of the NHS-treated samples, differences in the variance of dose-matched treatment groups with and without neutrophils were assessed for significance by two-way repeated-measures ANOVA (variance between treatment groups, $P < 0.001$ for both 10 μg and 40 μg sets; variance comparing neutrophil status, $P = 0.135$ and $P = 0.058$, respectively) with results of Sidak’s multiple-comparisons tests displayed in the graph. (D and E) Reactive oxygen species production by human neutrophils exposed to preopsonized MMC39, as measured by luminol luminescence, in the presence of NHS (D) or fetal bovine serum (FBS) (E). The left time lapse graphs are representative of five independent experiments. Right bar graphs show aggregate data of the area under the curve (AUC) and the maximum rate of change (max Δ) relative to those for PBS for all experiments. Differences in AUC and max Δ between control Ab, mlgG1, and mlgG3 were assessed for significance by a Kruskal-Wallis test ($P < 0.01$ for NHS and FBS), with results of Dunn’s test for multiple comparisons displayed in the graph. For all in-graph statistics, $P$ values displayed in black are comparisons to the control IgG, whereas $P$ values in red compare mlgG1 with mlgG3. $P$ values are indicated with ns (not significant) if $P > 0.1$, * if $P < 0.05$, ** if $P < 0.01$, and *** if $P < 0.001$. 

FIG 3A Phagocytic Index

MMC39

Phagocytic Index

Control mlgG1 mlgG3

33576

Phagocytic Index

Control mlgG1 mlgG3

33576Δ

Phagocytic Index

Control mlgG1 mlgG3

FIG 3B Representative Images

Control mlgG4 mlgG3

FIG 3C Bacterial Survival

MMC39 + NHS

Bacterial Survival (Percent CFU)

mAb Dose NHS PMN

Control 40 μg/ml 10 μg/ml 10 μg/ml 40 μg/ml

mlgG3 ns ns ns ns

mlgG1 ns ns ns ns

mlgG2 ns ns ns ns

FIG 3D Reactive Oxygen Species Production

MMC39 + NHS

Reactive Oxygen Species (Luminescence)

PBS IgG Control IgG1 IgG3

Control mlgG1 mlgG2 mlgG3

FIG 3E Reactive Oxygen Species Production

MMC39 + FBS

Reactive Oxygen Species (Luminescence)

PBS IgG Control IgG1 IgG3

Control mlgG1 mlgG2 mlgG3

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mune activation, while the mlgG3 antibody generally exhibited reductions of these markers in neutropenic mice (Fig. 4B).

We proceeded to compare subclass efficacy at a lethal infectious dose, which has been previously observed to cause dissemination to the liver and spleen and death within 72 h. At this dose, both subclasses performed equally in nondepleted mice, reducing lung, liver, and spleen burden by at least 1 log (Fig. 4C). However, within neutropenic mice, mlgG1 showed some loss of efficacy, reducing lung burden by only 0.52 log. Meanwhile mlgG3 continued to reduce burden in all three organs by over 1 log. **Figure 4** Antibody-mediated protection against CR-Kp pulmonary infection in control and neutrophil-depleted mice. (A) Bacterial burden in the lungs of C57BL/6 mice depleted of neutrophils (Ly6G) or administered a control antibody and subsequently infected with a nonlethal inoculum of MMC39 preopsonized with 17H12 subclasses or controls. Each symbol represents one mouse. (B) Cytokine levels, normalized to total lung protein, of mice in panel A, measured by a Bio-Plex panel. (C) Bacterial burden in lungs, liver, and spleen of depleted and nondepleted mice infected with a lethal inoculum of preopsonized MMC39. For all studies, overall differences in CFU and cytokines between treatment groups and between neutrophil status were assessed for significance by two-way ANOVA. Individual comparisons made between treatment groups of mice of the same neutrophil status (* symbols above), or comparisons made between wild-type or neutropenic mice given the same inoculum (# symbols below) were tested using Tukey's post hoc test with P values displayed in the graph. P values are replaced with ns (not significant) if P > 0.1, * if P < 0.05, ** if P < 0.01, or *** if P < 0.001. P values below plots compare CFU or cytokine levels of wild-type and neutropenic mice within the same treatment group.
log, though results were more variable. Cytokine levels were also more variable as expected, although global increases in inflammatory cytokines such as granulocyte-macrophage colony-stimulating factor (GM-CSF), IL-6, and IL-17 were observed compared to the nonlethal dose (Fig. S4). These cytokines appeared to drop in the presence of either subclass.

Overall, we observed protection of both antibodies in both immunocompetent and neutropenic mice, with a slight advantage of the mlgG1 subclass in mediating small localized infection. At higher doses, both subclasses demonstrated equal efficacy in healthy mice, while only mlgG3 subclass showed significant efficacy in neutropenic mice.

**DISCUSSION**

Though the pharmaceutical industry has focused primarily on development of hlgG1 antibodies, there are increasing efforts to compare the efficacy of different antibody isotypes and subclasses in treating both cancer and infectious disease (29–31). Despite mlgG2a and mlgG3 being most similar to hlgG1, direct comparisons between mlgG1 and mlgG3 exclusively have provided important insights into antibody-mediated resolution of infection (12, 32, 33). Studies investigating antcapsular antibodies against *Cryptococcus neoformans*, for example, have suggested that mlgG3 is poorly suited to protect against infection compared with mlgG1 (34, 35), whereas protection in mice from *Bacillus anthracis* spores was exclusively mediated by mlgG1 (8). Subclass-specific antibody interactions with *K. pneumoniae* have not been previously studied in detail. Although humoral responses to a CR-Kp hexasaccharide vaccine were predominantly mlgG1, mlgG3, like hlgG2, is the primary humoral response to T-independent antigens such as polysaccharide capsules and is the predominant antibody subclass identified after vaccination with full-length capsule (14, 37, 38). This suggests that mlgG3 has some evolutionary importance in protecting against encapsulated organisms.

While having identical variable regions, 17H12 mlgG1 and 17H12 mlgG3 differ in binding the CR-Kp capsular polysaccharide, inducing serum bactericidal activity, fixing complement, promoting phagocytosis, and promoting neutrophil-mediated bacterial reduction both in vitro and in vivo. The improved binding ability of mlgG3 subclasses has been previously observed in antibodies against *Burkholderia* and group A *Streptococcus* capsules (33, 39) and has been attributed to the ability of mlgG3 to self-aggregate, creating opportunities for cooperative binding and increased avidity (40, 41). Our binding and agglutination data extend this knowledge to antcapsular antibodies against CR-Kp, although we observed an intermediate level of binding after F(ab’)_2 digestion of mlgG3, whereas others have observed mlgG3 F(ab’)_2 fragments to have no better binding than mlgG1 fragments (33, 39). This difference may be due to greater contribution of the mlgG3 hinge region or disulfide bonds to *K. pneumoniae* CPS epitopes (40), and further digestion of the antibody into Fab fragments or replacement of heavy chain domains may shed more light on these interactions (8). Nonetheless, aggregation and cooperative binding appear to be important in defending against encapsulated organisms, since in addition to mlgG3 and cold agglutinin IgM, the T-independent subclass hlgG2 has also demonstrated the ability to self-aggregate (42). Such properties, however, make preparations of monoclonal antibodies exceedingly difficult to purify and store.

Additionally, agglutination of the 33576 strain by our antibodies suggest that clade 2 CPS functional epitopes could be conserved across geographic location. Our previous studies were restricted to wzi154 clinical isolates collected in the greater New York City area (14, 22). Although further study of the wzi154 and other ST258 epitopes is warranted, such evidence adds more confidence to efforts to develop cross-protective antibodies and vaccines.

Several studies have shown the resistance of CR-Kp strains to serum and the efficacy of antibodies in overcoming this resistance (14, 15, 22, 43). Observing serum bactericidal activity is important when comparing antibody-mediated activity against CR-Kp.
Our results reiterate previous findings that mlgG3 Abs promote greater serum killing, as well as C3c and C5b-9 deposition, than mlgG1 Abs can. Fixation of complement by mlgG3 has been shown to be mediated by its CH2 domain (44), and the poor ability of mlgG1 to fix complement has also been observed (45, 46). As previously found and also demonstrated in this study, the capsule is imperative to CR-Kp survival in blood (15). Thus, mlgG3 may be more advantageous in limiting CR-Kp hematogenous dissemination through complement fixation.

The relative contributions of macrophages, monocytes, and neutrophils to CR-Kp clearance has been disputed. While evidence using cell-specific depletions in mice strongly suggested that lung clearance of CR-Kp is predominantly mediated by CCR2-positive macrophages over neutrophils (25), studies examining the role of human and primate neutrophils in CR-Kp clearance have shown their efficacy in clearing bacteria in vitro (15, 27, 47). These contributions matter significantly to the field of anti-infective antibody therapy in the context of CR-Kp, as up to 86% of patients with CR-Kp bacteremia are neutropenic, and these patients have been found to face worse prognoses than patients without neutropenia (19, 23). Our findings demonstrate that 17H12 mlgG1 may promote improved phagocytosis of CR-Kp relative to that promoted by 17H12 mlgG3, in murine J774 cells, as well as similar phagocytosis in bone marrow-derived macrophages. This is interesting, as these antibodies are thought to act via different receptors on the macrophage surface (32, 48). Nevertheless, phagocytosis of two CR-Kp strains did not correlate with killing of the bacteria, as CFU and visual evidence indicated that once inside, the CR-Kp was able to evade killing by the macrophage, and indeed to multiply within the cell. This phenomenon was also observed previously in non-CR K. pneumoniae strains, which were demonstrated to inhibit phagolysosome fusion (49). It is possible that coordination of macrophages with additional immune cells and cytokines may be required for the full capability of antibody-mediated opsonophagocytosis to be realized (50–53). Additionally, alveolar macrophages or inflammatory monocytes may have improved lysosomal capabilities relative to standard BMDMs (54), or macrophages may clear phagocytized bacteria self-destruction via autophagy or pyroptosis (50, 51).

Our studies in human neutrophils showed that mlgG3 promoted better clearance of CR-Kp by neutrophils at lower concentrations in the presence of serum. However, while antibody-mediated killing of CR-Kp by neutrophils depended on serum, the production of ROS upon stimulation with CR-Kp was not, as demonstrated with the production of ROS with heat-killed FBS-enriched media. Such findings suggest that ROS released by neutrophils in response to CR-Kp may be reactionary without being protective; further studies examining ROS responses in vivo, as well as studies examining other neutrophil protection mechanisms, such as lysosomal activity and neutrophil extracellular trap release, are warranted.

Our in vivo data provides several important findings. First, as previously stated, we observed CFU in the lungs of MMC39-infected mice to be higher in the neutrophil-depleted mice in both sublethal and lethal challenges, suggesting that neutrophils are indeed important in protection against pulmonary infection by this wzi154 isolate. This runs counter to other studies that found no change in CFU in lungs of neutropenic mice (25, 28). Our laboratory has previously discovered variability in the virulence of ST258 strains, including within wzi154 strains (22), and additional work has determined that neutrophils can clear some ST258 strains (47). Therefore, it is possible that immune responses to different CR-Kp strains may differ and thus be responsible for these differences.

Additionally, we observe potential differences in protection by the different subclasses. While both antibodies reduced bacterial burden in the lungs of mice, 17H12 mlgG1 performed better, and the mlgG1 was associated with higher levels of inflammatory cytokines in neutropenic mice than those in the control-treated or mlgG3-treated mice when given a sublethal dose. We suggest that at low inocula, monocytes and macrophages may be more important for infection control, and as mlgG1 showed better opsonophagocytosis, it may function as the better subclass in these mice. As
IgG and Antibody-Mediated Protection against CR-Kp

mentioned, bacterial control by macrophages could be augmented by other immune populations such as gamma delta T cells and innate type III lymphocytes, all of which may produce IL-17 to potentiate Klebsiella immunity (28, 55, 56). Increased levels of IL-17, IL-12, and other cytokines in the neutropenic mice may thus compensate for neutrophil responses through action by macrophages, monocytes, and other cells. IL-17, produced by resident lymphocyte populations, has been identified as indispensable in protection against K. pneumoniae pulmonary infection (28, 55–58). However, these neutrophil-independent responses may be insufficient at higher inocula, as evidenced by the reduction of mlgG1 efficacy in the neutropenic mice challenged with lethal infection. In contrast, drops in inflammatory cytokines in mlgG3-treated neutropenic mice may indicate that other components, such as complement, may be sufficient to control infection and require fewer compensatory distress cues for local control. Complement has been shown to be important in lung clearance of other pathogens early in infection (59, 60). Furthermore, retention of efficacy by mlgG3 in the high-inoculum neutropenic scenario may suggest a large role of complement in defending against more disseminated infection, when local control of infection by macrophages and other resident populations may be insufficient to compensate for the role of neutrophils. Studying subclass using complement depletion models may provide additional insights into the relative contribution of complement in antibody-mediated protection.

Our study has several limitations. First, large heterogeneity in virulence exists between K. pneumoniae isolates, even within CR-Kp subsets (22), and our contrasting findings regarding neutrophil protection highlight the need to further study heterogeneity of the pathogen-immune response in numerous CR-Kp isolates (25). Furthermore, the functions of individual monoclonal antibodies, even those with the same subclass and similar target, can also be heterogeneous. Some anticapsular Streptococcus pneumoniae antibodies are better able to promote opsonophagocytosis, while others may directly interfere with bacterial signaling and growth (61, 62). Therefore, future studies of CR-Kp anticapsular antibodies should investigate several to better sample their potential. Finally, future studies of anti-CR-Kp antibodies must innovate the field of in vivo models used to study CR-Kp infection, as convenient and effective models that reproduce the chronic, persistent infection caused by CR-Kp in humans have been difficult to develop (27).

In conclusion, we find that the subclass differences of an anticapsular antibody can affect various facets of immune function against carbapenem-resistant Klebsiella pneumoniae but can exhibit similar efficacy in vivo. This information will promote future monoclonal antibody work on CR-Kp to provide effective therapies, and supports the potential of antibody 17H12 as a candidate to further study. Furthermore, we observe a role for neutrophils in antibody-mediated protection in vivo, encouraging further efforts to investigate the pathogen-host interactions of CR-Kp.

MATERIALS AND METHODS

Ethics statement. Animal study protocols were approved by the Animal Committee (IACUC) at Stony Brook University in accordance with the Guide for the Care and Use of Laboratory Animals, the Animal Welfare Act, the Public Health Service Policy on Human Care and Use of Laboratory Animals, and all other local, state and federal regulations. Healthy serum and neutrophil donors gave written informed consent for blood donation under institutional review board (IRB) protocol 718744 at SBU.

Bacteria and growth conditions. Klebsiella pneumoniae MMC5, MMC34, and MMC39 are wzi154 clinical isolates, and MMC36 and MMC38 are wzi29 and wzi50 isolates, respectively, from Montefiore Medical Center and were described previously (22). SBU32 and SBU34 are clinical isolates from Stony Brook University Hospital previously used to study 17H12 mlgG3 (14). Strain 33576 and its capsule-deficient mutant (33576 Δwzi) were graciously provided by Barry Kreiswirth (15). For all experiments (unless otherwise noted), strains were grown at 37°C shaking to the mid-exponential phase in Miller LB broth from a 1:100 dilution of an overnight culture. Overnight cultures were derived from single colonies picked from a Miller LB plate no older than 30 days. Unless stated otherwise, cultures were washed with PBS twice before use.

Generation of pProbe-KtBl and transformation of CR-Kp MMC39. We previously utilized a pPROBE-ktGFP plasmid with a pV5 backbone and with GFP under the control of an inserted nptII kanamycin promoter (26, 63). We used this plasmid and, under contract with Genewiz, inserted the sequence of the sh ble gene, which conveys resistance to bleomycin, into a ClaI cut site positioned...
between the ori and the existing kkat cassette. Insertion of the gene was confirmed both by sequencing and by digest with BsuRI, which both the original pCPROBE-K and the shIgG1 gene possessed. The plasmid was transformed into MMC39 by electroporation and plated onto Lennox (low-salt) LB with pH adjusted to 8.0 and containing 50 μg/ml bleomycin (Zeocin; Thermo Fisher). Transformation was confirmed by growing positive colonies on 50 μg/ml bleomycin and 50 μg/ml kanamycin and observing GFP fluorescence of selected colonies under a microscope. To test for plasmid stability, we tested replicate plating of 100 unselected colonies onto selective plates, all of which grew. Additionally, nearly all bacteria screened after 10 serial exponential cultures of MMC39 in the absence of antibiotics were shown to be GFP-positive (GFP+1) by microscopy. For all later experiments, MMC39-GFP isolates were streaked onto Miller LB agar supplemented with 50 μg/ml of kanamycin and grown in kanamycin-supplemented Miller LB broth.

**Subclass switch production and sequencing.** The mIgG1 switch variant of the 17H12 mIgG3 murine hybridoma was generated as previously described (12). Briefly, the mIgG3 parent hybridoma line was treated with endotoxin and IL-4, and spontaneous switch variants were identified through enzyme-linked immunosorbent spot (ELISpot). Sib selection was initially utilized, followed by two rounds of fluorescence-activated cell sorting (FACS) of cells stained with fluorescein isothiocyanate (FITC)-conjugated rat anti-mouse IgG1 (catalog no. 1144-02; SouthernBiotech), and by rounds of soft-agar cloning in SeaPlaque agarose. Vials of frozen hybridoma clones were sent to GenScript for variable region exon sequencing and analysis through the IMGT/V Quest program.

**Antibody purification.** Antibodies were produced weekly over 6 months from respective hybridomas grown in CELLine (Wheaton) flasks fed with high-glucose Dulbecco’s modified Eagle’s medium (DMEM) plus 10% NCTC medium and 1× penicillin-streptomycin and 1× nonessential amino acids, supplemented with either 10% or 5% FBS in the inner and outer chambers, respectively. These antibodies were produced using protein G affinity chromatography per the manufacturer’s instructions. Eluted antibody was neutralized in Tris-HCl (pH 8.0) and NaCl to final concentrations of 100 mM and 300 mM, respectively, then concentrated by centrifugal filtration (Amicon 30K), filter sterilized, snap-frozen in liquid nitrogen, and stored at −80°C until use. Concentration was determined by absorbance at 280 nm (extinction coefficient = 1.4), which correlated with Bradford assay results.

**F(ab)′2 generation.** Fab′ fragments of the 17H12 mIgG1 and mIgG, were generated and purified using the Pierce Fab′ preparation kit and mouse IgG, Fab′/F(ab)′2, preparation kits following the manufacturer’s instructions, except for digestion temperature and duration (10 min at ambient temperature for mIgG, and 36 h at 37°C for mIgG1). Coomassie staining of SDS-PAGE in nonreducing conditions was utilized to ensure MAb/F(ab)′2 purity after all purifications/digestions.

**Binding affinity.** The EC50 of the MAb/F(ab)′2 fragments was calculated using ELISA as described previously (26). Briefly, polystyrene plates (Corning 3690) were coated with 0.5 mg/ml of ST258 clade 2 CPS (MMC34) in PBS, then blocked with 1% PBS-bovine serum albumin (BSA). The MAbS or F(ab)′2 fragments were serially diluted starting at 1 μM [assuming molecular weights (MW) of 150 kDa for full IgG and 110 kDa for Fab′(1)′2 unpublished results] and proceeding 2-fold. Antibody was detected using a horseradish peroxidase (HRP)-conjugated goat anti-mouse IgG kappa secondary antibody (1:1,000, catalog no. PA1-86015; SouthernBiotech) and with 1-Step Turbo TMB (N,N′,N′,N′-tetramethyl-1,3-butanediamine) ELISA substrate (Thermo Fisher) according to the manufacturer’s instructions. Between steps, wells were washed four times with PBS-0.1% Tween 20. Experiments were repeated on two different days with two different antibody purification batches and digests to ensure reproducibility. Control antibodies were run in parallel as negative controls (catalog no. 0102-01 and 0105-01; SouthernBiotech).

**Serum resistance assays.** Serum resistance/killing assays were modified from a previously described assay (22). Briefly, 250 μl of a 1×10^8 CFU/ml solution was added to 750 μl of PBS containing 20% fresh or heat-inactivated (HI) human serum from a healthy donor. HI serum was generated from donor serum by a 30-min incubation in a 57°C water bath. Tubes were incubated at 37°C, rotating end over end. At 0, 60, and 120 min after mixing, 100 μl was sampled from each tube, diluted, and plated onto LB agar for CFU quantitation. Percent survival was measured as a fraction of the CFU count at 0 min.

**Complement deposition assays.** Flow cytometry was used to detect complement deposition of C3c and C5b-9, as previously described (14). Briefly, bacteria were diluted to 1×10^8 CFU/ml in 1 ml PBS-BSA 1% or 20% fresh human serum (in PBS-BSA), PBS or 10 μg/ml of antibody was then added, and bacteria were incubated either 20 min or 40 min at ambient temperature for C3c and C5b-9 deposition, respectively. Bacteria were washed, resuspended in PBS-BSA, and incubated with either...
FITC-conjugated sheep anti-human C3 (catalog no. AHP031F; Bio-Rad) at 1:500 or AF488-conjugated mouse anti-C5b-9 (aet11) (catalog no. S120AF488; Novus Biologicals) at 1:150 or without antibody for 20 min at 4°C. After incubation, bacteria were washed and analyzed for fluorescence by FACSCalibur. Integrated geometric mean fluorescence was measured as the product of the percentage of gated events that passed a fluorescence threshold and the mean fluorescence of those events that passed the threshold.

**Macrophage phagocytosis assays.** BMDMs were differentiated from frozen bone marrow from 6 week-old c57BL/6 mice (Taconic) as previously described (66), except using pure macrophage colony-stimulating factor (M-CSF) (10 ng/ml) rather than L929 medium as the M-CSF source for feedings on days 1 and 4. Differentiation of cells was confirmed by flow cytometry on cells stained with FITC-conjugated anti-F4/80 and BV5-1-conjugated CD11b (purity; >98% double positive). Macrophage phagocytosis as measured by CFU was performed similarly to previous protocols (22, 26). Briefly, 1 × 10⁶ BMDM or J774A.1 cells were incubated overnight in wells of cell culture-treated 96-well plates. BMDMs were cultured in RPMI with HEPES and L-glutamine supplemented with 10% FBS and 1× nonessential amino acids, while J774A.1 cells were cultured in DMEM supplemented with 10% FBS, 10% NCTC-109, and 1× nonessential amino acids. The following day, 1 × 10⁸/ml bacteria were opsonized for 20 min in respective cell culture media containing 40 µg/ml of either mlG2a, mlG3, or control mlG1, and 100 µl of this (multiplicity of infection [MOI] = 10) was added to each well of the washed macrophage plates. After 30 min of incubation at 37°C in 5% CO₂, cells were washed thrice and exposed to medium with 100 µg/ml of polymyxin B for 20 min. Cells were washed again, and time 0 wells were immediately lysed twice with water and plated, while those at later time points remained in culture medium until needed. All conditions were performed in triplicate wells. The number of CFU calculated from LB plates was divided by the number of estimated cells plated to give the phagocytic index. Microscopy was performed using the MMC39-GFP strain and EVOS FL Auto (40× objective; Thermo Fisher) using phase contrast and a GFP light cube.

**Neutrophil killing assays.** Neutrophil assays were adapted from a previous protocol (15). Briefly, 5 × 10⁶ bacteria opsonized for 30 min at RT in RPMI medium containing appropriate antibody concentrations were added to 5 × 10⁶ human neutrophils in RPMI medium containing a final concentration of 5% autologous fresh or HI serum. At 0, 15, 30, and 60 min, 100 µl were sampled from reaction tubes, lysed in cold PBS plus 0.1% Triton X-100, diluted in PBS, and plated on LB agar for CFU quantitation. Percent survival was measured as a fraction of the CFU count at 0 min. Tubes containing sera but not neutrophils were used as controls. All conditions were performed in triplicate wells. The number of CFU calculated from LB plates was divided by the number of estimated cells plated to give the phagocytic index. Microscopy was performed using the MMC39-GFP strain and EVOS FL Auto (40× objective; Thermo Fisher) using phase contrast and a GFP light cube.

**Pulmonary infection experiments.** We used c57BL/6 mice (Taconic) aged 7 to 9 weeks for all mouse experiments, and pulmonary infection was performed as previously (14, 67). At 48 and 4 h prior to the procedure, mice were injected intraperitoneally with 225 µg of rat anti-mouse Ly6G (1A8) or a control rat anti-mouse IgG2a (2A3) (BioXcell). Neutrophil depletion was confirmed previously using flow cytometry on cells stained with FITC-conjugated anti-mouse IgG2a, Ly6C⁻, CD11b⁻. Incuba were prepared by resuspending MMC39 in a Tris-glycine buffer containing 5 mg/ml of an ovalbumin control mlG2 (Crown Biosciences), 17H12 mlG2, or 17H12 mlG3, to a final concentration of 6 × 10⁶ or 3 × 10⁶ CFU/ml. After 1 h of opsonization, 50 µl of the inoculum was instilled into the surgically exposed trachea of a mouse under ketamine/xylazine using a bent 27-gauge needle. After 20 h, mice were euthanized, and lungs, liver, and spleen were collected and processed in NP-40 or PBS and diluted to enumerate CFU. Supernatants of lung homogenates (Ly6G⁻, Ly6C⁻) were analyzed for cytokines using the MMC39-GFP strain and EVOS FL Auto (40× objective; Thermo Fisher) using phase contrast and a GFP light cube.
acapsular mutant. We also thank Bruna Sco and Peter Seeberger for their initial contributions to the project. Additionally, we thank Anne Savitt for her assistance in editing the manuscript.

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