Structural Differences between the Two Human Complement C4 Isotypes Affect the Humoral Immune Response

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Summary

An animal model has been used to address the question of the biological importance of the known structural difference between the two isotypes of human C4, i.e., C4A and C4B. Guinea pigs deficient in C4 were reconstituted transiently with either human C4A or C4B protein and immunized with the bacteriophage ϕX174. Results from this study showed that C4A-reconstituted animals made a secondary response, i.e., switch from IgM to IgG; whereas the C4B-reconstituted animals did not.

MHC class I and class II proteins are highly polymorphic so as to increase the efficiency of binding to a wide range of peptides for antigen presentation (1-3). Of the class III proteins in humans, the fourth component of complement (C4) is also highly polymorphic, and >35 allotypes have been recognized (4-6). Null alleles of C4 are also common with a frequency of 0.1-0.3 in various populations as the result of gene deletions, gene conversions, and silent mutations (7-10). Comparison of the derived amino acid sequence of two common alleles of the C4A and C4B loci indicates that they are nearly identical with only 11 base substitutions, of which 10 are clustered within a small region of the α chain of C4, namely C4d (11, 12). Of these 10 base changes, six appear to be isotypic and the remaining allotypic based on serological determinants.

Porter (13) proposed that the polymorphism of C4 was important in binding to a wide range of antigens or antibodies. In a primary response, recognition of antigen by natural antibody is amplified by activation of the classical pathway of complement (14). An early step in this pathway is cleavage of C4 to C4b by the proteinase activity of C1. This exposes a highly reactive internal thioester, which is readily hydrolyzed by water unless a suitable acceptor is available; a covalent bond (either amide or ester) is then formed via a transacylation reaction (15). The efficiency of binding depends on the allotype of C4 and the chemical nature of the antigen or antibody. In general, allotypes of C4A bind preferentially to free amino groups of proteins, whereas those of C4B form ester bonds with carbohydrate or side chains of hydroxyl-containing amino acids, i.e., Ser, Thr, or Tyr (16, 17). This apparent selectivity appears to be the result of electrostatic and steric interactions between the isotypic region (residues 1101-1106) in the α chain of C4 and the acceptor molecule as shown by site-directed mutagenesis (18).

To determine if the selectivity of the two isotypes would affect the biological function, C4-deficient guinea pigs (C4Def g.p.'s) were reconstituted transiently with either human C4A or C4B protein and immunized with bacteriophage ϕX174. Results from this study show that transient reconstitution with C4A but not C4B induced a secondary response characterized by IgM to IgG switching.

Materials and Methods

Plaque and Neutralization Assays. The neutralization assay described by Ochs et al. (19) was performed. In general, serum was diluted by 10 × serial dilutions in phage buffer, and 100 μl was added to an equal volume of phage (150 PFU) and incubated at 37°C for 60 min. As a control, test dilution is plated immediately after adding phage and Escherichia coli. Subsequently, test sera and phage are added to E. coli in soft agar and plated. PFU are counted after a 3-h incubation at 37°C. Results are evaluated by a reciprocal of the dilution required to neutralize 50% of PFU. IgM and IgG were distinguished based on the sensitivity of the former to mercaptoethanol. Test sera are incubated overnight in 0.1 M mercaptoethanol before assay.

Immunization Protocol. Male C4 Def/N g.p.'s (inbred strain originated from a National Institutes of Health colony) of ~750 g were used for this study. MHC-matched strain 13 g.p.'s (obtained from NIH) of equivalent weight were used as normal controls. For nega-

Abbreviation used in this paper: C4Def g.p., C4-deficient guinea pig.
tive serum control, C4 Def/N g.p.'s were bled before immunization. g.p.'s were injected (intracardiac) with a dose of 2 × 10^9 PFU/kg for both the primary and secondary (4 wk later) immunizations. For transient reconstitution, antigen was mixed with 2.5 mg of human C4A or C4B in 1 ml of sterile PBS or 3 ml of normal g.p. serum (strain 13) before injection. Approximately 0.5 ml of blood was taken within 30 min of injection via puncture of the retro-orbital sinus to test for circulating phage and C4 activity.

**Purification of Human Complement C4.** Human C4 was purified by using a two-step procedure of affinity chromatography (mAb specific for C4 β chain was a gift from Dr. Paul Levine, Washington University School of Medicine, St. Louis, MO) and fractionation of inactive from active C4 by FPLC mono-Q as described by Dodds and Law (20). The separate isotypes were purified from plasma of individuals typed as deficient in either C4A or C4B. The affinity columns were prepared by coupling protein A-purified antibody to affinity gel 10 (Bio-Rad Laboratories, Richmond, CA) using manufacturer's protocol. C4 was eluted at high pH (pH 10.5) as described (20). Eluted fractions were directly fractionated on a 1-ml mono-Q column (Pharmacia Fine Chemicals, Piscataway, NJ) using a FPLC apparatus and active C4 eluted using a gradient of 0.1–0.5 M NaCl in 20 mM Tris/Cl, pH 7.2. Pooled C4 was assayed for hemolytic activity, and aliquots were stored at −80°C. The relative amounts of active C4, i.e., 2.5 mg, were determined by calculating Z U/ml (1 Z U = −ln [1−fractional lysis]) for each isotype and comparing with a standard plasma sample of C4A/C4B. Since C4B is about fourfold more active in this assay than C4A, the number of units was corrected for the difference. Thus, an equivalent number of units of C4A and C4B could be determined. As an independent assay, the purified C4 was treated with Cls, and the products were analyzed on SDS-PAGE gels. The level of activity could be determined as inactive C4 α chain is insensitive to cleavage with Cls as described previously (18). The hemolytic assay used was the same described previously (18).

**Results**

**Reconstitution of C4Def g.p. with Human C4 Protein.** Previous studies have shown that the impaired immune response of C4Def g.p.'s (21) would be restored by injection of 3 ml of normal g.p. serum at the time of primary immunization (19, 22). An equivalent amount of human C4 was determined to be 2.5 mg based on results from an hemolytic assay in vitro (data not shown). To determine if human C4 would be inactivated or cleared at a rate different from g.p. C4, C4Def g.p.'s were reconstituted with 2.5 mg of human C4A, C4B, or 3 ml of normal g.p. serum, and the level of C4 activity was determined over 48 h. The results in Fig. 1 show that the two isotypes of human C4 decayed at a similar rate, which was similar to that of g.p. C4. The lower hemolytic activity of C4A compared with C4B reflects the four- to fivefold difference in binding of C4A to the antibody-coated red cell surface (16, 17).

**Clearance of Antigen after Primary and Secondary Immunization.** C4Def g.p.'s were injected intravenously with a mixture of 2 × 10^9 PFU of bacteriophage φX174/Kg and either 2.5 mg of human C4A, C4B, or 3 ml of normal g.p. serum. As controls, C4Def and strain 13 g.p. were administered antigen only (see diagram in Fig. 2). The presence of active C4 and bacteriophage in the circulation after the injection was confirmed by analysis of blood samples, which were taken within 30 min postimmunization.

Clearance of the bacteriophage after the primary and secondary immunization was followed by analyzing serum samples taken at intervals over the first 48 h. After the primary immunization, the phage were cleared to background by 48 h at a similar rate for all animals (Fig. 3 a). In contrast, a distinct difference in clearance among the groups was observed after the second immunization 4 wk later (Fig. 3 b). The level of circulating phage was <10 PFU/ml in strain 13 animals within the first 0.5 h of the injection of antigen. Comparison of the reconstituted C4Def g.p.'s at 0.5 h showed...
Figure 3. (a) Clearance of bacteriophage after primary immunization with bacteriophage φX174. Note that results from reconstitution of C4-deficient g.p. reconstituted with human C4A are not included in the comparison. (b) Clearance of bacteriophage after secondary immunization. Animals were bled within 30 min of injection of phage and then at 5, 24, and 28 h.

Figure 4. (a) Primary and secondary humoral immune response to φX174. Animals were injected intravenously with $2 \times 10^9$ PFU/kg of body weight and with or without C4 (see inset for treatment) at day 0. Secondary immunization was administered with antigen only at week 4. Animals were bled at 1-wk intervals through week 8, and total antibody titer was determined using the plaque neutralization assay. (b) Secondary (IgG) immune response to φX174. Animals were treated as above, except sera from weeks 4–7 were treated with 0.1 mM mercaptoethanol overnight before neutralization assay.
that the titer of phage circulating in the C4A animals was about two logs less than that of those treated with C4B. At 5 h postinjection, the level of phage was <10 PFU/ml in C4A, whereas the C4B had a titer of ~10^4 PFU/ml. Thus, a significant difference in antigen clearance was observed after the secondary challenge with antigen.

Primary and Secondary Humoral Immune Response. Animals were bled each week after the primary and secondary immu-

Table 1. Primary and Secondary Humoral Immune Response

| Guinea pig     | Primary response* (week 1) | Secondary response* (week 5) | Standard error† | p value$ | C4A vs. C4B |
|----------------|----------------------------|-----------------------------|-----------------|---------|-------------|
|                |                            |                             | week 1 week 5   |         |              |
| C4Def g.p.     | 173                        | 40                          | 100             |         |             |
|                | 168                        | 100                         | 200             |         |             |
|                | 169                        | 100                         | 100             |         |             |
|                | 121                        | 10                          | 40              |         |             |
|                | 112                        | 10                          | 200             |         |             |
|                | 113                        | 10                          | 10              |         |             |
|                | Mean                       | 45                          | 180             | 18      | 33          |
| C4Def g.p. + C4A | 119                    | 400                         | 1,000           |         |             |
|                | 171                        | 500                         | 1,000           |         |             |
|                | 143                        | 200                         | ND              |         |             |
|                | 144                        | 200                         | 2,000           |         |             |
|                | Mean                       | 325                         | 1,333           | 75      | 340         |

| C4Def g.p. + C4B | 153                     | 50                          | 200             |         |             |
|                | 154                        | 50                          | ND              |         |             |
|                | 126                        | 100                         | 200             |         |             |
|                | 128                        | 50                          | 100             |         |             |
|                | Mean                       | 62                          | 167             | 12.5    | 33.5        |

| C4Def g.p. + n.g.p.s. | 151                     | 200                         | 400             |         |             |
|                      | 152                        | 200                         | ND              |         |             |
|                      | 170                        | 400                         | 200             |         |             |
|                      | 163                        | 400                         | 6,000           |         |             |
|                      | 164                        | 400                         | 200             |         |             |
|                      | Mean                       | 320                         | 1,700           | 50      | 1,430       |

| Normal g.p.        | 125                        | 200                         | 2,000           |         |             |
|                    | 115                        | 800                         | 5,000           |         |             |
|                    | 172                        | 800                         | 10,000          |         |             |
|                    | Mean                       | 600                         | 5,667           | 200     | 2,350       |

* Antibody titer is the reciprocal of serum dilution resulting in 50% neutralization of phage.
† SEM of titer at weeks 1 and 5.
$ Comparison of the standard errors of C4A and C4B using student's t test.
was observed in the primary immune response of the C4A
week, the titer of all C4Def g.p.s dropped to background;
pattern was observed after the second injection at week 5.  
In Fig. 4 a and Table 1, a significant (p < 0.02) difference
serum dilution resulting in 50% neutralization). As shown
using a phage neutralization assay (titer = reciprocal of the
mean titer of C4A was ~800. As reported by others, recon-
stituted with C4A or those untreated. By the second
week, the titer of all C4Def g.p.'s dropped to background;
whereas the titer of strain 13 g.p.'s was still detectable and
increased slightly over the next 2 wk. A dramatically different
pattern was observed after the second injection at week 5.  
The mean titer of the C4A (1,333 ± 340 SEM) was about
eightfold greater than that of C4B (167 ± 33.5 SEM), which
was significant (p < 0.03). Over the next 2 wk the mean
titer of C4B had dropped to near background; whereas the
mean titer of C4A was ~800. As reported by others, recon-
stitution of C4Def g.p.'s with normal g.p. serum also restored
their immune response (see Table 1).

To confirm that the apparent secondary response of C4A
animals was a memory response, i.e., switch from IgM to
IgG, aliquots of serum were treated with 2-ME before the
phage neutralization assay. The IgM but not the IgG frac-
tion of specific antibody should be sensitive to the treatment
and no longer neutralize the phage (19). Although the mean
titer of the reconstituted g.p.'s was lower, the pattern observed
was similar to the untreated sera (Fig. 4 b). At week 5, the
mean titer of C4A-reconstituted g.p.'s was about eightfold
greater than those reconstituted with C4B, and it dropped
only slightly over the next 2 wk as is characteristic of a sec-
ondary response. For the same time period, the mean titer
of C4B animals dropped to background as seen in the pri-
mary immune response. As expected, the C4Def g.p.'s re-
constituted with normal g.p. serum also switched from IgM to
IgG; whereas the untreated C4Def g.p.'s failed to secrete a
detectable level of IgG.

Discussion

Assays in vitro had shown that the two isotypes of human
C4 protein differed dramatically in binding to hydroxyl (car-
bohydrate) and amino groups (protein) (16, 17). However,
it was not clear if this difference would affect the role of C4
in the immune response in vivo. To address this question,
C4Def g.p.'s were reconstituted with either human C4A or
C4B, and their humoral immune response to bacteriophage
antigen was examined.

Comparison of animals reconstituted transiently with ei-
ther C4A or C4B showed a dramatic difference in both their
clearance of antigen and their humoral immune response after
the secondary challenge with antigen. The C4A-reconstituted
animals not only cleared the phage antigen quicker, they also
produced a memory response, whereas C4B-reconstituted
animals did not. The most probable explanation for the differ-
ence in secondary response is that reconstitution with C4A
resulted in a more efficient activation of B lymphocytes in
the primary immune response. It seems unlikely that enhance-
ment of the immune response was due to a differential inter-
action between the isotypes and the g.p. immune system;
because the C4A and C4B proteins decay at a similar rate
in the C4Def g.p.'s (Fig. 1) and they interact similarly with
g.p. components of classical pathway as demonstrated by the
reconstitution of C4Def g.p. serum.

In light of the selective difference in binding between the
two C4 isotypes, the phage capsid surface would provide a
more suitable acceptor surface for C4A than C4B. Its icos-
ahedral capsid is thought to be assembled from repeating units
of the F protein (48 kD) and three smaller spike proteins,
and it does not appear to bear carbohydrate (23). The dia-
gram in Fig. 5 provides a model illustrating the putative in-
teraction of nascent C4b (activated C4) with antigen and nat-
ural antibody (IgM) in a primary immune response. In this
model, binding of nascent C4b to antigen depends on steric
and electrostatic interactions between the C4 polymorphic
region and the antigen (18). Allotypic variation, which occurs
in the same region (11, 12), may also be important in the
binding reaction.

It is interesting that after the secondary challenge the strain
13 animals cleared the antigen to near background within
30 min (earliest time point) (Fig. 3 b). The pronounced dif-
ference in clearance between the strain 13 and C4A-reconstituted
g.p.'s reflects, in addition to a difference in phage-antibody
titer, the importance of immune adherence (24, 25), which
is mediated by the classical pathway. In the transiently recon-
stituted animals, clearance was probably mediated by anti-
body and cells bearing Fc receptors since the human C4
was no longer active at week 4. However, a role for the alter-
native pathway of complement, which is intact and can be acti-
vated by immune complexes (26), could not be ruled out.
Since the clearance of phage was based on a biological plaque
assay, it is possible that circulating phage were present in the
test serum but were not active. However, this possibility seems
unlikely at least in the C4Def g.p.'s in light of the low titer
of antiphage antibody measured before the secondary chal-
lenge with antigen. The finding that the ratio of IgG to IgM
was much lower in the C4A animals than strain 13 also sug-
gests the importance of an intact classical pathway for a normal
memory response. As observed by others (19, 22), the C4Def

Figure 5. Model of binding of nascent C4b to antigen in the pri-
mary immune response after act-
vitation by C1. Efficiency of coval-
ent binding of C4b is determined
by steric and electrostatic interac-
tions between the polymorphic re-
region of C4 and the antigen.
g.p.'s reconstituted with normal g.p. serum also developed a secondary response. Individuals homozygous for deficiency in C4A or C4B are more at risk to certain diseases than those expressing both isotypes (27). For example, susceptibility to infection with encapsulated bacteria segregates with homozgous deficiency in C4B rather than with C4A (28, 29). However, homozygous deficiency in C4A is a major risk factor for systemic lupus erythematosus (30, 31). According to the hypothesis of Porter (13), these associations reflect the distinct binding preferences of the two isotypes. The functional difference found in this study provides the first support in vivo for this hypothesis.

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