Sequence Homology of the Diabetes-associated Autoantigen Glutamate Decarboxylase with Coxsackie B4-2C Protein and Heat Shock Protein 60 Mediates No Molecular Mimicry of Autoantibodies

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Summary

Molecular mimicry between viral antigens and host proteins was often suggested to be involved in induction of autoimmune diseases. In type 1 diabetes where pancreatic β cells are destroyed by autoimmune phenomena, a linear sequence homology between a major autoantigen, glutamate decarboxylase (GAD), and the 2C protein of coxsackie B4 was identified. In addition, a sequence homology between GAD and the mycobacterial heat shock protein 60 was described and the suggestions were made that molecular mimicry between GAD, coxsackievirus B4-2C protein, and/or heat shock protein 60 (hsp60) may be actively involved in an autoimmune reaction towards the pancreatic β-cells. Our group was the first to isolate human monoclonal autoantibodies to GAD (MICA 1-6) from a patient with newly diagnosed type 1 diabetes. The MICA allowed a detailed characterization of the diabetes associated self-epitopes in GAD and represent a set of GAD autoantibodies present in sera from patients with type 1 diabetes. Using deletion mutants of GAD we demonstrated that the regions of GAD covering the homology sequences to coxsackievirus B4 and to the hsp60 were absolutely required for binding of the MICA to GAD. We now designed an antibody-based analysis to ask whether molecular mimicry between GAD and coxsackie B4-2C or hsp60 is relevant in type 1 diabetes. Since part of the MICA recognize conformational epitopes, they allow to test for conformational molecular mimicry in viruses that have been incriminated in the development of type 1 diabetes. Our data reveal no crossreactivity between the diabetes associated GAD epitopes defined by the MICA and hsp60, rubella virus, cytomegalovirus, and coxsackie B1-B6 virus antigens. Neither coxsackie B4-specific antibodies in sera from normal individuals nor GAD-positive sera from patients with type 1 diabetes indicated a crossreactivity between coxsackie B4-2C and GAD. Although the regions in GAD homologous to coxsackie B4-2C and hsp60 represented parts of GAD indispensable for binding of diabetes associated autoantibodies they did not mediate a crossreactivity of autoantibodies between GAD and these two proteins. No evidence for molecular mimicry between GAD and a whole panel of foreign antigens was detected by autoantibodies in type 1 diabetes.
In type 1 (insulin-dependent) diabetes mellitus (IDDM) where pancreatic β cells are destroyed by an autoimmune process, many unrelated viruses have been implicated in the induction of the disease (5). Only in children with congenital rubella syndrome has a clear correlation between virus infection and the high incidence of IDDM emerged (6). Recent findings related the high frequency of IDDM in individuals with congenital rubella syndrome to molecular mimicry effects, since a mouse monoclonal antibody revealed crossreactivity between a rubella virus capsid protein and a 52-kD islet antigen (7). A major, well-characterized autoantigen in type 1 diabetes is the enzyme glutamate dehydrogenase (GAD) (8) which exists in two forms, GAD₆₅ and GAD₆₇, only one of which, GAD₆₅, is expressed in human islets (9). GAD is recognized by autotobodyes as well as autoreactive T cells (10, 11). Recently, Kaufman et al. (12) reported a sequence homology between GAD₆₅ and the 2C protein of coxsackievirus B₄ (CB₄) and Jones et al. (3) described a sequence homology of GAD₆₅ to the mycobacterial and the human hsp₆₀ (Fig. 1 A). This raised the question whether molecular mimicry between GAD₆₅ and these proteins is actively involved in induction of IDDM.

We recently derived human monoclonal autoantibodies to GAD₆₅ (MICA 1-6) from a patient with newly diagnosed IDDM, which allowed a detailed characterization of diabetes associated epitopes in GAD₆₅ (13, 14). In studies with deletion mutants of GAD₆₅, the regions of GAD covering the homology sequences to CD4 were absolutely required for binding of MICA 1, 3, 4, and 6. Although the N-terminal amino acids 1-244 could be removed from the GAD molecule without affecting binding of the MICA, the removal of an additional 50 amino acids, which included the homology region to CB₄, prevented binding of MICA 1, 3, and 4, and 6, and of all GAD-positive IDDM sera tested with this GAD deletion mutant (Fig. 1 B). The homology region of hsp₆₀ was required for a binding of MICA 1, 2, and 3 to the GAD₆₅ molecule (14). Although MICA 1, 3, 4, and 6 recognized conformational epitopes, the linear sequence homology region may provide a crucial part of the epitope. Since the MICA epitopes represent a set of diabetes associated epitopes, these antibodies provide a unique tool to investigate the existence of molecular mimicry between GAD₆₅ and proteins of CD4 or hsp₆₀. In addition, for the first time in humans, the MICA allow complex viral antigens to be probed for conformational molecular mimicry effects with GAD₆₅, that may escape detection in sequence alignment studies. We here analyzed a panel of viruses previously implicated in the development of IDDM for molecular mimicry with diabetes-associated GAD₆₅ epitopes and studied in greater detail the possible crossreactivity of CB₄-2C and GAD₆₅ epitopes using GAD-positive sera from patients with IDDM and CB₄-positive sera from normal individuals. Our data give no evidence for a crossreactivity between GAD₆₅ and the CB₄-2C protein on the antibody level. Neither hsp₆₀ nor viral antigens of rubellavirus, cytomegalovirus, and coxsackievirus B₁-B₆ displayed molecular mimicry to the diabetes-specific GAD₆₅ epitopes defined by the MICA.

Materials and Methods

Viruses and Cell Lines. The vero, HeLa, and HEL cell lines were obtained from the American Type Culture Collection (Rockville, MD) and SP₂ cells from Invitrogen (San Diego, CA). The GMK cell line and the picornaviruses used in this study have been described before (15). Coxsackieviruses and respective titers were: B₁ (P. O. Dalladorf) 10⁸.₅ TCID₅₀/ml, B₂ (Ohio 1) 10¹⁰.₅ TCID₅₀/ml, B₃ (Nancy) 10¹⁰ TCID₅₀/ml, B₄ (Nz-1-pp) 10⁹ TCID₅₀/ml, B₅ (Faulkner) 10⁶.₇ TCID₅₀/ml, B₆ (1-51-21) 10⁵.₉ TCID₅₀/ml. The viruses were propagated on GMK cells (16) and harvested for antigen preparation after 24 h by repeated freezing and thawing followed by ultrasonification on ice 3 x for 15 s. Cell debris was removed by low speed centrifugation and infectivity titer were assayed by endpoint titration on GMK cells and/or by plaque assay. Uninfected GMK cells processed in parallel served as control antigen. Cytomegalovirus was an isolate from a patient who received bone marrow transplantation. Virus was grown in HEL cells and harvested by Dounce homogenization of the cells after cytopathic effects became visible. Cell debris was removed by centrifugation at 3000 g for 10 min. Infectivity titer was 3 x 10⁴ TCID₅₀/ml. Uninfected cells processed in parallel served as control antigens. Rubella virus antigen was purchased from Behringwerke AG (Marburg, Germany).

Antibodies. The MICA were derived from a patient with IDDM as described (13). They were of the IgG class and recognized at least three distinct epitopes specific for GAD₆₅ (13). MICA 2 recognized a linear epitope in GAD that was rare in the sera of patients with IDDM, whereas MICA 1, 3, and 4 and 6 recognized conformational epitopes similar to those detected in GAD-positive sera from patients with IDDM (14). Mouse anti-hsp₆₀ antibody II C 8 ascites was obtained from T. Gillis (Marshall University School of Medicine, Huntington, WV), the CB₄-specific mouse monoclonal antibody M₁ was produced by one of us (17), and rabbit anti-2C antibody by C. Hohenadl (Max-Planck-Institute of Biochemistry, Martinsried, Germany) (18).

Patients Sera and Test for CB₄ Antibodies. Sera from 42 normal individuals, 22 healthy schoolchildren, and 15 newly diagnosed patients with IDDM were obtained with informed consent. CB₄-specific IgM responses were detected by μ-antibody capture ELISA technique employing CB₄ antigens and monospecific mouse
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brane fraction of GAD₆₅ expressing Sf9 cells and mock infected as described (21). The protein was purified by anion-exchange chromatography (21).

Preparation of GAD₆₅. The human recombinant GAD₆₅ sequence was cloned into a baculovirus expression vector and recombinant virus isolated as described (22). A detergent solubilized membrane fraction of Sf9 cells expressing GAD₆₅ and mock infected Sf9 cells was prepared according to (10).

Immunoprecipitation Assay. 2 × 10⁶ Sf9 cells were infected by recombinant baculovirus expressing human GAD₆₅, 40 h after infection cells were labeled for 4 h with 100 μCi [³⁵S]methionine. CB₄-proteins were labeled 4 h after infection of 6 × 10⁷ HeLa cells with 3.6 × 10⁹ plaque forming units of CB₄ by incubation of the cells with 150 μCi [³⁵S]methionine in methionine-free modified Eagle’s medium. After washing cells were lysed and extracts prepared as described above for unlabeled GAD₆₅. Samples of cytoplasmic extracts of infected HeLa cells or solubilized membrane fractions of Sf9 cells expressing GAD were preclarified by incubation with 25 μL CB₄-negative pool serum. To include CB₄ antibodies of the IgM class in our analysis, 25 μL test serum was incubated over night with the preclarified extract and the immune complexes were precipitated using protein A-Sepharose coated with a goat anti-human IgM-specific antibody (1:1, 2 h, 4°C). The immune complexes were washed in 100 mM Tris, 500 mM LiCl, 1% NP-40, 0.5% mercaptoethanol, and bound antigen was eluted by addition of 62 mM Tris/HCl, pH 6.8, 2% SDS 5% mercaptoethanol, 0.01% bromophenol blue and subjected to polyacrylamid gel electrophoresis. Bound protein was detected after fluorography.

Immunoblotting and Western Blotting. Virus antigens, GAD₆₅ (0.63 mg/ml) and the appropriate controls were tested pure and in dilutions of 1:20 and 1:50. 50 μL of each extract were spotted on polyvinylidene difluoride (PVDF) membranes (Immobilon; Millipore Corp., Bedford, MA) using a slot blot apparatus (Schleicher & Schuell Inc., Keene, NH). Proteins separated on polyacrylamid gels were transferred to PVDF by blotting. Blotting membranes were stained by 0.2 h with MICA culture supernatants (2 μg/ml), human monoclonal IgG control antibody (2 μg/ml), rabbit anti-2C antibody (1:100), mouse anti-hsp60 II C 8 ascites (1:400) or supernatant of the CB₄-specific mouse monoclonal antibody M1 (17) (undiluted).

Results

Reactivity of MICA 1–6 with Viral Antigens. Viral antigens from coxsackie B1–B6, cytomegalovirus, rubellavirus and herpes simplex virus and rubellavirus were tested for their reactivity with the individual MICA in an immunoblotting assay using the native antigens. Extracts of uninfected host cells, GAD₆₅ expressed in baculovirus permissive Sf9 cells and wild-type baculovirus infected Sf9 cells expressing no GAD were included as controls (Fig. 2). Whereas spotted GAD₆₅ was detected by all six MICA, neither the viral antigens nor the controls were recognized by MICA 1–6. CB₄ antigens were specifically stained by the CB₄-specific mouse monoclonal antibody M1 used as a positive control.

Reactivity of GAD₆₅ 1–6 with hsp₆₀. Different dilutions of a GAD₆₅ extract and of purified hsp₆₀ from M. bovis BCG were analyzed in a slot blot assay (Fig. 3). The MICA did not crossreact with the hsp₆₀ suggesting that the GAD₆₅ region of amino acids 520–534, which is homologous to hsp₆₀, is not directly involved in the epitope recognition of MICA 1, 2, and 3 which required this region of GAD for binding. Alternatively, the homology between the two proteins is too weak to induce crossreactivity by an autoantibody isolated from a patient with type 1 diabetes.

Reactivity of CB₄-positive Sera with GAD₆₅. We further analyzed whether CB₄ infection in humans induced antibodies crossreactive with GAD₆₅. 15 sera positive for CB₄ IgM antibodies in the ELISA and 15 CB₄ IgM-negative sera from normal individuals, 22 sera from normal individuals with neutralizing antibodies to CB₄, and 20 normal sera negative for neutralizing CB₄ antibodies were tested for their reactivity with GAD in an immunoprecipitation assay using [³⁵S]-labeled GAD₆₅ expressed in a baculovirus system. A combined analysis of IgM and IgG antibodies was performed for the CB₄ IgM-positive sera. The results are summarized in Table 1. No reactivity with GAD₆₅ was observed with all sera. When seven CB₄-IgM-positive and eight CB₄-IgM-negative sera from patients with IDDM were tested in the same assay, no correlation was found between the CB₄-reactivity and the GAD-reactivity of these sera. CB₄ infection, therefore, did not induce antibodies crossreactive with GAD₆₅ and GAD antibodies appeared independent of positivity for CB₄ in patients with IDDM.

![Figure 2](antibody任教1-6 with viral antigens. Viral antigens of coxsackie B1-B6, cytomegalovirus, rubellavirus, and herpes simplex virus were spotted on membrane sheets and tested for their reactivity with the MICA. CB4 4 was selected as example for the typical reactivity of all MICA that stained solely GAD. The anti-coxsackievirus B4 (CB4)-specific control antibody M1 reacted with the CB4 antigen only and an unrelated human monoclonal IgG antibody revealed no reactivity with the tested virus antigens. Positions of the antigens: 1a, CB1; 2a, CB2; 3a, CB3; 4a, CB4; 5a, CB5; 5b, CB6; 1c, 2b, 3b, mock infected GMK; 4b, GAD65; 5b, S9 control extract; 1c, Cytomegalovirus; 2c, mock infected HEL; 3c, mock infected Vero; 4c, herpes simplex virus, 5c rubellavirus.)

![Figure 3](antibody任教1-6 with hsp60 of M. bovis BCG. GAD65 was expressed in baculovirus Sf9 cells and a detergent solubilized membrane fraction of the cells (5 μg total protein/ml) was spotted on membranes together with purified hsp60 (2 μg/ml). For each antigen three dilutions were applied (from top to bottom: pure, 1:5, and 1:25). Lane a was stained by an unrelated human monoclonal antibody, lane b by MICA 2, lane c by the anti-hsp60-specific mouse monoclonal antibody IHC, and lane d by an unrelated mouse monoclonal antibody. All six MICA showed identical results.)
Table 1. Correlation of Anti-coxsackie B4 (CB4)-reactive Antibodies with Anti-GAD-reactive Antibodies in Normal Individuals and Patients with IDDM

<table>
<thead>
<tr>
<th>Individuals</th>
<th>No. of sera tested</th>
<th>GAD65positive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB4 IgM positive*</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>CB4 IgM negative</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>CB4 NA positive†</td>
<td>22</td>
<td>0</td>
</tr>
<tr>
<td>CB4 NA negative</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>IDDM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB4 IgM positive</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>CB4 IgM negative</td>
<td>7</td>
<td>4</td>
</tr>
</tbody>
</table>

* Anti-CB4 IgM antibodies were determined by ELISA.
† NA, neutralizing antibodies were determined by a microtechnique in GMK cells.

Reactivity of GAD-positive Sera with CB4-2C. MICA 1–6 and 10 GAD-positive sera from 10 newly diagnosed patients with IDDM as well as 10 sera from normal individuals positive for neutralizing CB4 antibodies and 2 individuals negative for CB4 were analyzed for their reactivity with CB4-2C. HeLa cells were infected with CB4 and labeled by [35S]methionine incorporation. Extracts of CB4 infected HeLa cells were immunoprecipitated with the MICA or the individual sera after preclearing with a CB4-negative serum. Precipitation of viral antigens was detected after separation of the samples by PAGE. No reactivity of the MICA with CB4 antigens was detected (Fig. 4A) concordant with the results presented in Fig. 2. In contrast, all sera recognized a whole panel of bands irrespective of their positivity in the CB4-specific ELISA or the neutralizing test. To determine whether 2C was among the proteins precipitated by the sera, the immunoprecipitates were subjected to Western blotting and stained with an anti-2C rabbit serum raised against a 20-amino acid consensus epitope of the 2C protein of coxsackie B viruses (18). The results are shown in Fig. 4. 3 of the 10 GAD-positive sera from patients with IDDM revealed a reactivity with the 2C protein as well as 3 of 10 GAD-negative sera tested from normal individuals. The frequency of anti-2C antibodies was, therefore, identical in GAD-positive individuals with IDDM and GAD-negative normal individuals. This suggests no correlation of an anti-2C response with autoreactivity to GAD in patients developing type 1 diabetes.

Discussion

Since the isolation of CB4 particles from islets of a patient who died with acute onset of IDDM and the induction of diabetes in mice infected with these particles, CB4 infections were frequently claimed to be correlated with IDDM. In nonhuman primates and some mouse strains CB4 infections produced transient diabetes (23, 24), but in humans the large number of serological and epidemiological studies revealed no clear picture of an implication of CB4 infection in IDDM (reviewed in 5). After identification of the 64-kD islet antigen as GAD (8) a sequence homology between this major autoantigen in diabetes and the 2C protein of CB4 was identified (12). Molecular mimicry effects between GAD and CB4, therefore, were suggested to play a role in islet cell destruction and development of IDDM. We isolated six diabetes-associated GAD-specific human monoclonal autoantibodies, four of which required the CB4 homology region in GAD65 for a binding to the GAD65 molecule (14). Now we demonstrate that these antibodies do not crossreact with native
CB4 antigens and particularly not with the 2C protein. The linear sequence homology region shared between GAD65 and CB4-C2, although being an important part of the conformational epitopes of MICA 1, 3, 4, and 6 did not mediate a crossreactivity between both proteins.

The coxsackievirus 2C protein is a nonstructural virus protein that is produced by the infected cell did not incorporated in the infectious particle itself. 2C may have a function in the replication of viral RNA (25) and is highly conserved among coxsackieviruses B1–B6 (26). Sera from normal individuals irrespective of positivity for neutralizing anti-CB4 antibodies or anti-CB4-IgM-ELISA antibodies all recognized CB4 virus proteins. The fact that the two sera negative for antibodies to CB1-CB6 still recognized a pattern of CB4 antigens may be due to the presence of antibodies to other picornaviruses that are known to be highly crossreactive to coxsackie antigens (16, 27). Reactivity to the viral protein 2C was detected in 30% of CB4-positive normal individuals by Western blotting. GAD-positive sera of patients with type 1 diabetes revealed the same frequency of an anti-2C response like GAD-negative normal individuals. This argues against a crossreactivity between CB4-2C and GAD65 progressing to a development of type 1 diabetes in susceptible individuals. Neither the CB4-specific antibodies in sera of CB4 positive individuals nor GAD antibodies in IDDM, therefore, provided any evidence that tolerance to the linear epitope of GAD which is homologous to CB4-2C was broken. This suggests no molecular mimicry effects between GAD65 and the CB4-2C protein in the humoral immune response of type 1 diabetes.

Controversial data exist about the implication of hsps in the development of IDDM (28, 29). One group reported that hsps60 was among the antigens recognized by the diabetes associated 64-kD antibodies (28). Other groups, however, clearly demonstrated that 64-kD antibodies recognize GAD (8) and detected no anti-hsp60 antibodies in sera from patients with IDDM (29). In spite of the reported sequence similarity between GAD and hsps60 (Fig. 1) (3) we demonstrated herein that the observed sequence homology did not induce crossreactivity by a set of human monoclonal autoantibodies. In an animal model of IDDM, the NOD mouse, T cell clones reactive to mycobacterial hsp60 have been shown to induce insulitis and hyperglycemia (30). The T cell–reactive peptides in hsps60 were confined to amino acids 437–474, and were, therefore, different from the homology region observed between hsps60 and GAD65. Neither the T cell epitopes in hsps60 characterized in the NOD mouse system nor the typical set of diabetes associated autoantibodies in humans tested here, therefore, suggest any relevance for molecular mimicry effects between hsps60 and GAD65 in type 1 diabetes.

The humoral antibody response in humans tested here suggests no relevance for molecular mimicry effects between GAD65, the CB4-2C protein, hsps60, and other virus antigens which have been suggested to be involved in induction of type 1 diabetes. No data are available about possible T cell–mediated molecular mimicry to GAD in humans as T cell reactive epitopes in GAD remain to be determined. In NOD mice the late activation of T cells to the CB4 homologous region in GAD provides evidence against the hypothesis that molecular mimicry between CB4 and GAD65 triggers the autoimmune response on the T cell level in this animal model of IDDM (31). We agree with others that direct destruction of islet cells by viruses (32), upregulation of MHC class I molecules (33, 34), induction of an inappropriate MHC class II expression on islets (35), enhancement of cytokine production in the periphery of islets after virus infections (33, 34), or a combination of these mechanisms may be the relevant factors leading to IDDM in a critical immunogenetic background rather than molecular mimicry effects between viral antigens and GAD65.

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