OPEN ACCESS

University of BRISTOL

Peer reviewed version

University of Bristol - Explore Bristol Research

General rights

Detection of antibodies directed to the N-terminal region of GAD is dependent on assay format and contributes to differences in the specificity of GAD autoantibody assays for type 1 diabetes

Short running title: Improved specificity of autoantibodies to N-terminally truncated GAD

Alistair JK Williams[1], Vito Lampasona[2], Michael Schlosser[3], Patricia W Mueller[4], David L Pittman[5], William E Winter[5], Beena Akolkar[6], Rebecca Wyatt[1], Cristina Brigatti[2], Stephanie Krause[7], Peter Achenbach[7] and Participating Laboratories

1. School of Clinical Sciences, University of Bristol, Bristol, UK
2. Division of Genetics and Cell Biology & Diabetes Research Institute, IRCCS San Raffaele Scientific Institute, Milan, Italy
3. Department of Medical Biochemistry and Molecular Biology and Institute of Pathophysiology, University Medical Center of Greifswald, Karlsburg, Germany
4. Molecular Risk Assessment Laboratory, Centers for Disease Control and Prevention, Atlanta, GA, USA
5. Department of Pathology, University of Florida, Gainesville, FL, USA
6. Division of Diabetes, Endocrinology, and Metabolic Diseases, National Institute of Diabetes and Digestive and Kidney Diseases, Bethesda, MD, USA
7. Institute of Diabetes Research, Helmholtz Zentrum München, and Forschergruppe Diabetes, Klinikum rechts der Isar, Technische Universität München, Neuherberg, Germany

Correspondence to –
Alistair Williams
Diabetes and Metabolism, School of Clinical Sciences
Learning and Research Building, Southmead Hospital
Bristol BS10 5NB
Fax: +44 117 323 5336   Tel: +44 117 414 7900
A.J.K.Williams@bristol.ac.uk

Word count: 2836   Figures: 4

Supplemental figures: 3   Supplemental table: 1   Supplemental appendix: 1

ABSTRACT

Autoantibodies to glutamate decarboxylase (GADA) are sensitive markers of islet autoimmunity and type 1 diabetes. They form the basis of robust prediction models and are widely used for recruitment of subjects at high risk of type 1 diabetes to prevention trials. However GADA are also found in many individuals at low risk of diabetes progression. To identify the sources of diabetes irrelevant GADA reactivity therefore, we analyzed data from the 2009 and 2010 Diabetes Autoantibody Standardization Program GADA workshop and found that binding of healthy control sera varied according to assay type. Characterization of control sera found positive by radiobinding assay, but negative by ELISA showed that many of these sera reacted to epitopes in the N-terminal region of the molecule. This finding prompted development of an N-terminally truncated GAD_{65} radiolabel, ^{35}S-GAD_{65}(96-585), which improved the performance of most GADA radiobinding assays (RBAs) participating in an Islet Autoantibody Standardization Program GADA substudy. These detailed workshop comparisons have identified a source of disease-irrelevant signals in GADA RBAs and suggest that N-terminally truncated GAD labels will enable more specific measurement of GADA in type 1 diabetes.

Accurate prediction of type 1 diabetes depends on islet autoantibody measurement. The presence of autoantibodies directed against multiple islet antigens confers a high risk of disease (1; 2), and improved performance of individual islet autoantibody assays would enable more efficient recruitment of high-risk subjects to therapeutic prevention trials. Autoantibodies to glutamate decarboxylase (GADA) are the most widely used marker for type 1 diabetes, but to achieve optimum disease sensitivity the threshold for GADA positivity is often set at the 99th percentile, a level that exceeds the lifetime risk of developing the disease (3). Many individuals found GADA positive with current assays are therefore unlikely to progress to type 1 diabetes, making the development of more specific GADA assays a high priority (4).

The Diabetes Antibody Standardization Program (DASP) was established in 2001 with the aim of improving islet autoantibody assay performance and concordance among laboratories (5). DASP has facilitated the rapid evaluation and adoption of novel autoantibody assays (6-8) and this work continues under the mantle of the Islet Autoantibody Standardization Program (IASP). During the lifetime of DASP/IASP there have been major improvements in assay performance and comparability, but the specificity of GADA assays can still vary by as much as 10% between laboratories that achieve similar sensitivity (9).

Closer analysis of recent DASP/IASP workshops has revealed systematic differences in the reactivity of individual healthy control sera between ELISAs and radiobinding assays (RBAs). Several control sera showed increased binding of GAD_{65} in the majority of RBAs, despite being found negative in most ELISAs, while the converse was true for other control sera. We therefore investigated the binding characteristics of those control sera found positive

3

more commonly by RBA to identify sources of disease irrelevant signals and using this information, set out to develop more specific GADA assays.

RESEARCH DESIGN AND METHODS

DASP/IASP workshops

Analysis was performed on samples included in the 2009 and 2010 DASP workshops as well as a GADA substudy in the 2012 IASP workshop (Supplemental Fig. 1). In each workshop, laboratories received uniquely coded sets of blinded sera from 50 patients with newly diagnosed type 1 diabetes contributed by several centers around the world, together with up to 100 US blood donors without a family history of diabetes as healthy controls (Supplemental Table 1). Type 1 diabetes was diagnosed by local centers on the basis of clinical characteristics. All samples were collected within 14 days of starting insulin treatment. The 90 control sera included in DASP 2010 were also among the 100 control sera used in DASP 2009. Sera were prepared and frozen in 100 μL aliquots and distributed by the Centers for Disease Control and Prevention or University of Florida as previously described (10). Laboratories were asked to test samples for GADA using the assay formats of their choice, to provide details of their assay protocols, and to report assay results, including raw data, to DASP/IASP for analysis. Assays parameters varied between and within different formats. Major differences included the volume of serum used, buffer constituents, primary incubation time, separation method, washing technique and standardization method. To reduce variation between RBAs the standard method protocol was developed which fixed these aspects of the technique thereby allowing for greater comparability between laboratories (11). In the DASP 2009 workshop, 42 laboratories from 19 countries reported results for 56 GADA assays. In the DASP 2010 workshop, 39 laboratories from 19 countries reported results for 53 GADA

4

assays. In the IASP 2012 workshop, 10 laboratories from 7 countries participated in a GADA

substudy using non-commercial RBAs (Supplemental Appendix).

Assessment of epitope specificities

The epitope specificities of selected GADA workshop control sera were assessed using

plasmids encoding full length GAD_{65}, GAD_{67} and truncated GAD_{65}, as well as GAD_{65}-GAD_{67}

chimeras (12). GAD_{67}, $GAD_{67}(1\text{-}101)/GAD_{65}(96\text{-}440)/GAD_{67}(453\text{-}593)$, and $GAD_{67}(1\text{-}$

$243)/GAD_{65}(235\text{-}444)/GAD_{67}(453\text{-}593)$ were cloned into pGEM-Teasy (Promega), while

$GAD_{65}(1\text{-}95)/GAD_{67}(101\text{-}593)$ and $GAD_{67}(1\text{-}452)/GAD_{65}(445\text{-}585)$ were cloned into pGEM3

(Promega). $GAD_{65}(46\text{-}585)$ and $GAD_{65}(96\text{-}585)$ were cloned into pTnT (Promega). All

plasmids were provided by Vito Lampasona apart from the pTNT plasmid $pThGAD_{65}$

encoding full length GAD_{65} (courtesy of Ake Lernmark). Samples were assayed for GADA

using the standard assay protocol (11) with ^{35}S-methionine labeled antigens made by *in vitro*

transcription and translation of GAD_{65}-GAD_{67} chimeras, truncated GAD_{65} and full-length

GAD_{65}. To further characterize GADA binding, selected DASP 2010 workshop sera were

also assayed for GADA(1-585) and GADA(96-585) using the standard assay protocol with

and without addition of 5 or 0.05 pmol per well of recombinant full-length GAD_{65} (Diamyd

Medical AB, Stockholm, Sweden). Using this approach, median percentage displacement of

GADA binding was calculated as 100*(cpm label alone – cpm label with unlabeled

GAD)/cpm label alone) with a minimum set at 0%. Lack of displacement at 5 pmol/well

would indicate a lack of specificity for GAD_{65}, while lack of displacement at 0.05pmol/well

would suggest that the antibodies were of low affinity, especially when levels of binding were

low (13; 14).

For the IASP 2012 GADA substudy, participating laboratories generated ^{35}S-labeled GAD using the pTnT plasmid (Promega, Madison, USA) vector encoding GAD_{65}(96-585) distributed by Vito Lampasona, as well as their usual plasmid encoding full-length GAD_{65} or ^{125}I-labeled human recombinant full-length GAD_{65}. Prior to the GADA substudy, coded DASP 2010 sets were assayed by three selected laboratories using both ^{35}S-labeled GAD_{65}(96-585) and GAD_{65}(46-485) encoded in the same vector (Supplemental Figure 1).

Data analysis

Categorical variables were compared using the χ^2 test. Areas under the curve (AUCs) for the different assays from receiver operator characteristics (ROC) analysis were compared using the Wilcoxon signed rank test. When laboratory assigned positive-negative calls were analyzed according to assay format, only those assays with specificity above 90% were included. For all analyses, a two-tailed *P*-value of 0.05 was considered significant. Statistical analyses were performed using the Statistics Package for Social Sciences Version 19 (IBM, New York, USA).

RESULTS

The pattern of GADA reactivity in healthy individuals is associated with assay format

The median laboratory assigned sensitivities and specificities of GADA assays in the DASP 2010 workshop were 86% (range 34 to 92%) and 94% (range 68 to 100%), respectively. According to threshold independent measures (10), adjusted sensitivity at 95% specificity (AS95) and AUC, the commercial ELISA showed the best overall performance (Figure 1). When assay results were analyzed according to assay format the positive-negative calls for

control sera often clustered according to assay type (Figure 2a). For example, control serum LQ21235 was scored positive by 8 of 10 laboratories using the commercial ELISA, but none of the other assays. In contrast, control sera N51532, N56575, N59932, S8531 and N53371 were found positive by none of the laboratories using the commercial ELISA as compared to 19 (54%), 18 (51%), 13 (37%), 10 (29%) and 10 (29%) of the other 35 assays, respectively. Another difference between assays was that serum N54357 was scored positive by 6 of 8 RBAs using the commercial kit with iodinated GAD_{65} antigen, but none of the other 37 assays. In contrast to the pattern observed in controls, no clear assay-specific differences in the reactivity of patient sera were seen (data not shown).

Assays show a consistent pattern of reactivity over time

The pattern of positive-negative calls for control sera in the DASP 2009 workshop was very similar to that of DASP 2010 (Figure 2b). The serum found positive exclusively by ELISA in DASP 2010, LQ21235, was positive in all 9 ELISAs, but none of the other assays. The five sera found positive by none of the laboratories using the commercial ELISA but at least 30% of other assays in DASP 2010, were again consistently negative by ELISA and positive in 20 to 71 percent of other assays. Serum N54357 was positive in 6 of 11 commercial RBAs as well as the only other RBA using iodinated antigen, but in none of the other 38 assays.

Characterization of control samples called positive in DASP 2010

To determine whether the pattern of positivity in controls could be explained by differences in assay-specific reactivity to particular GADA epitopes, selected control samples were assayed by RBA using ^{35}S labelled GAD_{65}, GAD_{67} and $GAD_{65/67}$ chimeras (12) (Figure 3). Of the three samples found positive more often by ELISA, LQ19277 showed dominant binding to the N-terminal of GAD_{67} and weak binding to full-length GAD_{65}, while sera LQ21235 and

TS23727 recognized epitopes restricted to the N-terminal of GAD_{65} that were dependent on amino acids 46 to 95. However, as expected for a serum found positive exclusively by ELISA, LQ21235 showed very low levels of binding in these RBA experiments. Of the five control samples found positive more often by RBAs, three (N51532, N56575 and N59932) showed weak reactivity with the middle region of GAD_{65}. A fourth serum (S8531), showed reactivity restricted to the N-terminal of GAD_{65}. The fifth serum, N53371, bound predominantly to epitopes in the N-terminal region of GAD_{65} with weaker responses to GAD_{67}.

Specificity of binding to ^{35}S labelled GAD_{65}(1-585) and GAD_{65}(96-585) in these sera was confirmed by competitive displacement with excess (5 pmol per well) unlabeled GAD_{65}. Median displacement of GADA binding in all 8 sera was 60% (range 39% to 78%) with ^{35}S-GAD_{65}(1-585) and 72% (range 70% to 76%) in the three sera found positive with ^{35}S-GAD_{65}(96-585) (Supplemental Fig. 2a). This compares with a median displacement of binding in six GADA positive patients (IDS samples 004, 005, 006, 009, 097 and 195) of 87% (range 68% to 98%) and 91% (range 71% to 98%) for ^{35}S-labeled GAD_{65}(1-585) and GAD_{65}(96-585), respectively (Supplemental Fig. 2b).

To identify sera with low affinity antibodies, GADA binding was competed at a low concentration of unlabeled GAD_{65}. Competition with 0.05 pmol per well unlabeled GAD_{65} caused median displacement of binding by the six patient sera of 65% (range 40% to 86%) and 76% (range 61% to 87%) with ^{35}S-labeled GAD_{65}(1-585) and GAD_{65}(96-585), respectively (Supplemental Fig. 2d). In contrast, median displacement of binding in the three sera showing weak reactivity with the middle region of GAD_{65} (N51532, N56575 and N59932) was 0% (range 0% to 15%) with ^{35}S-labeled GAD_{65}(1-585) and 14% (range 9 to 24%) with ^{35}S-labeled GAD_{65}(96-585) indicating that these samples had low affinity antibodies (Supplemental Fig. 2c).

Evaluation of GADA assays using $GAD_{65}(46\text{-}585)$ and $GAD_{65}(96\text{-}585)$ plasmids

To investigate whether replacing $GAD_{65}(1\text{-}585)$ with N-terminally truncated GAD_{65} constructs could improve GADA assay performance, three laboratories assayed a new coded set of samples from DASP 2010 with ^{35}S labels generated using plasmids encoding $GAD_{65}(1\text{-}585)$, $GAD_{65}(46\text{-}585)$ and $GAD_{65}(96\text{-}585)$. In each laboratory the highest AS95 (88%) was achieved using the $GAD_{65}(96\text{-}585)$ construct (Supplemental Fig. 3).

Evaluation of $GAD_{65}(96\text{-}585)$ in the IASP 2012 GADA substudy

The potential of the $GAD_{65}(96\text{-}585)$ radiolabel to improve the performance of GADA RBAs was assessed by 10 laboratories in the IASP 2012 GADA substudy. Participating laboratories assayed coded IASP sets using both ^{35}S or ^{125}I labelled $GAD_{65}(1\text{-}585)$ and ^{35}S labelled $GAD_{65}(96\text{-}585)$. Of the 10 laboratories, 8 showed higher AS95 values with $GAD_{65}(96\text{-}585)$ (Figure 4). Changes in the AS95 with the $GAD_{65}(96\text{-}585)$ label ranged widely from -14 to +20%, showing that even within RBAs the reactivity of different sera is strongly influenced by local assay conditions.

DISCUSSION

Using data from DASP workshops we have shown that the binding of GAD_{65} by healthy control sera segregated according to assay format. Some control sera reacted preferentially in the commercial ELISA but not in the RBA, while others found positive in many RBAs showed no binding in ELISAs. A high proportion of the control sera found positive by RBAs targeted epitopes in the N-terminal region of GAD_{65} which are less commonly recognized by

diabetes-relevant antibodies (15-18). These findings prompted the construction of a plasmid

encoding GAD_{65}(96-585), suitable for generating N-terminally truncated radiolabel. In the

IASP 2012 GADA substudy, 8 of 10 RBAs using this plasmid achieved a higher adjusted

sensitivity than those using full-length GAD_{65}, indicating that the performance of many RBAs

could be improved by use of N-terminally truncated GAD radiolabels.

Earlier islet autoantibody workshops have shown differences in assay performance that could

be ascribed to particular characteristics. The higher sensitivity of IA-2 autoantibody assays

using plasmids expressing the intracellular region (ic) rather than the IA-2(256–556/630–979)

or full-length constructs led to more widespread adoption of IA-2ic autoantibody assays (10).

The clear superiority of RBAs over ELISAs for measuring insulin autoantibodies (IAA) has

meant that RBAs have been used almost exclusively for IAA measurement (19). The

differences we observed with GADA assay format were more subtle, but by focusing on

signals generated by healthy control sera, we were able to identify an important source of

disease irrelevant signals in the N-terminus affecting RBAs. Despite the superior overall

performance of the GADA ELISA, analogous modification of the capture antigen in the

ELISA format may improve the specificity of the assay. Even in the most robust GADA

ELISAs, false positive signals from sera acquired from healthy individuals contribute

significantly to the higher background levels of binding that define assay thresholds, limiting

our ability to assign true beta-cell autoimmunity.

Birth cohort prospective studies of relatives of patients with type 1 diabetes have shown that

diabetes relevant autoantibody epitope reactivity typically spreads from the C-terminal and

middle (PLP) regions to the N-terminal domains of the molecule (12; 16). Autoantibodies to

the N-terminal region typically constitute a relatively minor component of GAD_{65}

autoreactivity and alone confer little association with type 1 diabetes (17). However, we

cannot exclude the possibility that a very small proportion of sera from patients with type 1

diabetes may bind exclusively to the N-terminus and will be missed by the truncated antigen.

Furthermore, in patients with other forms of diabetes such as latent autoimmune diabetes in

adults or slowly progressive type 1 diabetes mellitus, epitopes in the N-terminal region may

constitute a larger proportion of the anti-GAD response (20; 21). The potential benefit of

using truncated antigen to test for these conditions therefore, needs to be evaluated. Cross-

reactive N-terminal restricted GADA may mark an early phase of autoimmunity in

neurological conditions such as Stiff Person Syndrome (SPS) (22-24), although as those

disorders are rare and SPS itself is associated with very high GADA titers (25), the low level

N-terminal restricted antibodies found in healthy controls are more likely attributed to cross-

reactivity of irrelevant antibodies.

The commercial ELISA showed good sensitivity and specificity in DASP and IASP

workshops (9). This assay relies on the autoantibody forming a bridge between immobilized

GAD_{65} on the plate and biotinylated GAD_{65} in solution with detection by streptavidin

peroxidase (26). Access to N-terminal epitopes may be hindered in this configuration

preventing the binding of the N-terminally restricted antibodies detected by many RBAs. This

could also partly explain why luminescence immunoprecipitation (LIPS) and

electrochemiluminescence (ECL) assays (27; 28), showed good specificity in recent

workshops. However, we cannot exclude that other mechanisms may be responsible for lack

of binding of these N-terminally restricted control sera in the ELISA. Some of the assay-

dependent differences in recognition of DASP/IASP control sera are likely to be related to

antibody affinity. The three control sera found reactive with the middle region of GAD in

RBAs, but negative by ELISA showed minimal displacement at low levels of competing GAD$_{65}$ which suggests that these sera contain low affinity antibodies. This may be why these antibodies were not detected by the commercial ELISA or the ECL assay, as the bridging format they employ favors the recognition of high affinity antibodies, which are more closely associated with diabetes progression (17; 29). The performance of RBAs using N-terminally truncated GAD$_{65}$ labels may therefore be further improved by including affinity measurements.

A major strength of this study was the availability of data from a number of DASP and IASP workshops which allowed us to identify consistent patterns in the reactivity of control sera according to assay format. The original design of the DASP workshops (10), with the inclusion of a relatively large number of control sera, has again been vindicated, as it allowed us to identify systematic differences in reactivity which would have been impossible with a smaller number of samples. These sample sets distributed to laboratories are however still limited with regard to sample number, as well as ethnicity, age and their cross-sectional nature. Other important systematic variations in GADA binding by healthy control sera may be identified in different cohorts. Furthermore, only 10 laboratories participated fully in the IASP 2012 GADA substudy, which restricted our ability to determine whether use of the GAD$_{65}$(96-585) label could enhance assay performance.

Measurement of GADA is fundamental to most strategies aimed at prediction and characterization of type 1 diabetes, but there has been concern that despite their high sensitivity GADA are often less closely associated with diabetes progression than other islet autoantibodies such as IA-2A and ZnT8A (30). The DASP and IASP workshops have

revealed assay-related differences in binding of GAD_{65} by control sera that should aid the development of more specific GADA assays. If the promise shown by the N-terminally truncated $GAD_{65}(96-585)$ antigen probe to improve the specificity of GADA RBAs without loss of sensitivity is confirmed in large prospective studies, we would advocate its adoption for population screening in combination with other islet autoantibodies to identify individuals at high risk of progression to type 1 diabetes.

AUTHOR CONTRIBUTIONS

A.J.K.W., V.L. and P.A. researched data; contributed to the discussion; and wrote the manuscript. M.S., P.W.M., D.P., W.E.W., R.W., C.B., and S.K. researched data, and reviewed/edited the manuscript. B.A. reviewed/edited the manuscript. A.J.K.W. is the guarantor of this work and, as such, had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

ACKNOWLEDGEMENTS

REFERENCES.

1. Bingley PJ, Gale EA: Progression to type 1 diabetes in islet cell antibody-positive relatives in the European Nicotinamide Diabetes Intervention Trial: the role of additional immune, genetic and metabolic markers of risk. Diabetologia 2006;49:881-890

2. Orban T, Sosenko JM, Cuthbertson D, et al.: Pancreatic islet autoantibodies as predictors of type 1 diabetes in the Diabetes Prevention Trial-Type 1. Diabetes Care 2009;32:2269-2274

3. Haller MJ, Atkinson MA, Schatz D: Type 1 diabetes mellitus: etiology, presentation, and management. Pediatr Clin North Am 2005;52:1553-1578

4. Liu E, Eisenbarth GS: Accepting clocks that tell time poorly: fluid-phase versus standard ELISA autoantibody assays. Clin Immunol 2007;125:120-126

5. Bingley PJ, Williams AJK: Validation of autoantibody assays in type I diabetes: Workshop programme. Autoimmunity 2004;37:257-260

6. Achenbach P, Schlosser M, Williams AJ, et al.: Combined testing of antibody titer and affinity improves insulin autoantibody measurement: Diabetes Antibody Standardization Program. Clin Immunol 2007;122:85-90

7. Schlosser M, Mueller PW, Achenbach P, Lampasona V, Bingley PJ: Diabetes Antibody Standardization Program: First evaluation of assays for autoantibodies to IA-2{beta}. Diabetes Care 2011;34:2410-2412

8. Lampasona V, Schlosser M, Mueller PW, et al.: Diabetes antibody standardization program: first proficiency evaluation of assays for autoantibodies to zinc transporter 8. Clin Chem 2011;57:1693-1702

9. Torn C, Mueller PW, Schlosser M, Bonifacio E, Bingley PJ: Diabetes Antibody Standardization Program: evaluation of assays for autoantibodies to glutamic acid decarboxylase and islet antigen-2. Diabetologia 2008;51:846-852

10. Bingley PJ, Bonifacio E, Mueller PW: Diabetes Antibody Standardization Program: first assay proficiency evaluation. Diabetes 2003;52:1128-1136

11. Bonifacio E, Yu L, Williams AK, et al.: Harmonization of glutamic acid decarboxylase and islet antigen-2 autoantibody assays for national institute of diabetes and digestive and kidney diseases consortia. J Clin Endocrinol Metab 2010;95:3360-3367

12. Bonifacio E, Lampasona V, Bernasconi L, Ziegler AG: Maturation of the humoral autoimmune response to epitopes of GAD in preclinical childhood type 1 diabetes. Diabetes 2000;49:202-208

13. Achenbach P, Guo LH, Gick C, et al.: A simplified method to assess affinity of insulin autoantibodies. Clin Immunol 2010;137:415-421

14. Curnock RM, Reed CR, Rokni S, Broadhurst JW, Bingley PJ, Williams AJ: 'Insulin autoantibody affinity measurement using a single concentration of unlabelled insulin competitor discriminates risk in relatives of patients with type 1 diabetes. Clin Exp Immunol 2012;167:67-72

15. Richter W, Shi Y, Baekkeskov S: Autoreactive epitopes defined by diabetes-associated human monoclonal antibodies are localized in the middle and C-terminal domains of the smaller form of glutamate decarboxylase. Proc Natl Acad Sci U S A 1993;90:2832-2836

16. Hoppu S, Ronkainen MS, Kulmala P, Akerblom HK, Knip M: GAD65 antibody isotypes and epitope recognition during the prediabetic process in siblings of children with type I diabetes. Clin Exp Immunol 2004;136:120-128

17. Mayr A, Schlosser M, Grober N, et al.: GAD autoantibody affinity and epitope specificity identify distinct immunization profiles in children at risk for type 1 diabetes. Diabetes 2007;56:1527-1533

18. Fenalti G, Hampe CS, Arafat Y, et al.: COOH-terminal clustering of autoantibody and T-cell determinants on the structure of GAD65 provide insights into the molecular basis of autoreactivity. Diabetes 2008;57:1293-1301

19. Greenbaum CJ, Palmer JP, Kuglin B, Kolb H: Insulin autoantibodies measured by radioimmunoassay methodology are more related to insulin-dependent diabetes mellitus than those measured by enzyme-linked immunosorbent assay: results of the Fourth International Workshop on the Standardization of Insulin Autoantibody Measurement. J Clin Endocrinol Metab 1992;74:1040-1044

20. Hampe CS, Kockum I, Landin-Olsson M, et al.: GAD65 antibody epitope patterns of type 1.5 diabetic patients are consistent with slow-onset autoimmune diabetes. Diabetes Care 2002;25:1481-1482

21. Kobayashi T, Tanaka S, Okubo M, Nakanishi K, Murase T, Lernmark A: Unique epitopes of glutamic acid decarboxylase autoantibodies in slowly progressive type 1 diabetes. J Clin Endocrinol Metab 2003;88:4768-4775

22. Butler MH, Solimena M, Dirkx R, Jr., Hayday A, De Camilli P: Identification of a dominant epitope of glutamic acid decarboxylase (GAD-65) recognized by autoantibodies in stiff-man syndrome. J Exp Med 1993;178:2097-2106

23. Kim J, Namchuk M, Bugawan T, et al.: Higher autoantibody levels and recognition of a linear NH2-terminal epitope in the autoantigen GAD65, distinguish stiff-man syndrome from insulin-dependent diabetes mellitus. J Exp Med 1994;180:595-606

24. Daw K, Ujihara N, Atkinson M, Powers AC: Glutamic acid decarboxylase autoantibodies in stiff-man syndrome and insulin-dependent diabetes mellitus exhibit similarities and differences in epitope recognition. J Immunol 1996;156:818-825

25. Piquer S, Belloni C, Lampasona V, et al.: Humoral autoimmune responses to glutamic acid decarboxylase have similar target epitopes and subclass that show titer-dependent disease association. Clin Immunol 2005;117:31-35

26. Brooking H, Ananieva-Jordanova R, Arnold C, et al.: A sensitive non-isotopic assay for GAD65 autoantibodies. Clin Chim Acta 2003;331:55-59

27. Burbelo PD, Hirai H, Issa AT, et al.: Comparison of radioimmunoprecipitation with luciferase immunoprecipitation for autoantibodies to GAD65 and IA-2beta. Diabetes Care 2010;33:754-756

28. Miao D, Guyer KM, Dong F, et al.: GAD65 autoantibodies detected by electrochemiluminescence assay identify high risk for type 1 diabetes. Diabetes 62:4174-4178

29. Bender C, Schlosser M, Christen U, Ziegler AG, Achenbach P: GAD autoantibody affinity in schoolchildren from the general population. Diabetologia 2014;57:1911-1918

30. De Grijse J, Asanghanwa M, Nouthe B, et al.: Predictive power of screening for antibodies against insulinoma-associated protein 2 beta (IA-2beta) and zinc transporter-8 to select first-degree relatives of type 1 diabetic patients with risk of rapid progression to clinical onset of the disease: implications for prevention trials. Diabetologia 2010;53:517-524

Figure 1. Adjusted sensitivity at 95% specificity (AS95) plotted against the area under the curve (AUC) from ROC analysis of GADA assays participating in the DASP 2010 workshop. Using these threshold independent measures, better performance is demonstrated by those assays located towards the top right hand corner (circled), a cluster that includes all the commercial ELISAs.

Figure 2. Heatmaps of laboratory defined positive-negative calls for (a) the 10 healthy control sera found positive most often in DASP 2010 and (b) the same sera in DASP 2009 for those assays with a laboratory defined specificity of more than 90% sorted according to assay type. Positive-negative calls were found to cluster according to assay type; sera shaded in blue were found positive most commonly by commercial ELISAs, those in yellow by RBAs and the serum shaded in orange by RBAs using ^{125}I-labeled GAD_{65}.

Figure 3. Epitope specificity of 8 healthy control sera from the DASP 2010 workshop that showed assay-related differences in reactivity. The left panel shows the different GAD constructs used to assess epitope specificity with regions derived from GAD_{65} in black and GAD_{67} in white. The right panel shows reactivity of the control sera with these GAD constructs and the epitope reactivity ascribed to those sera based on the pattern of binding with the different constructs. Four sera (S8531, N53371, TS23727, and LQ21235) showed reactivity with GAD_{65} N-terminal epitopes that was abolished by deletion of the first 95 amino acids. Three control sera (N56575, N51532 and N59932) showed weak reactivity with the MID region of GAD_{65} (aa 235-444) and this binding was not reduced by use of the N-terminally truncated labels.

Figure 4. AS95 for ten RBAs using ^{35}S or ^{125}I-GAD$_{65}$ (1-585) and ^{35}S-GAD$_{65}$(96-585) to measure workshop samples in the IASP 2012 GADA substudy. Improved performance of assays using the N-terminally truncated GAD is shown by the 8 laboratories that lie above the line of equivalence (hatched line).