Postprandial Blood Glucose

AMERICAN DIABETES ASSOCIATION

Individuals with diabetes are at increased risk of developing microvascular complications (retinopathy, nephropathy, and neuropathy) and cardiovascular disease (CVD). The Diabetes Control and Complications Trial (DCCT) (1) and U.K. Prospective Diabetes Study (UKPDS) (2) showed that treatment programs resulting in improved glycemic control, as measured by HbA1c, reduced the microvascular complications of diabetes. The effect of these treatment programs on reducing CVD was less clear. However, some epidemiological studies suggest that there may be a relationship between glycemic levels and CVD.

In the management of diabetes, health care providers usually assess glycemic control with fasting plasma glucose (FPG) and premeal glucose measurements, as well as by measuring HbA1c. Therapeutic goals for HbA1c and preprandial glucose levels have been established based on the results of controlled clinical trials. Unfortunately, the majority of patients with diabetes fail to achieve their glycemic goals. Elevated postprandial glucose (PPG) concentrations may contribute to suboptimal glycemic control. Postprandial hyperglycemia is also one of the earliest abnormalities of glucose homeostasis associated with type 2 diabetes and is markedly exaggerated in diabetic patients with fasting hyperglycemia.

Several therapies targeted toward lowering PPG excursions are now available and have been shown to improve glycemic control as measured by HbA1c. However, many questions remain unanswered regarding the definition of PPG and, perhaps most importantly, whether postprandial hyperglycemia has a unique role in the pathogenesis of diabetic complications and should be a specific target of therapy. To address these issues and to provide guidance to health care providers, the American Diabetes Association (ADA) convened a consensus development conference on 24–26 January 2001 in Atlanta, Georgia.

A seven-member panel of experts in diabetes, endocrinology, and metabolism heard selected abstracts and presentations from invited speakers. The panel was then asked to develop a consensus position on the following questions:

1. How is PPG defined?
2. What is the relationship among PPG, FPG, and HbA1c?
3. What is the contribution of PPG to the long-term complications of diabetes?
4. Under what circumstances should people with diabetes be tested for PPG?
5. What are the benefits and risks of specifically lowering PPG in an effort to achieve better glycemic control?
6. What additional research needs to be performed to clarify the role of PPG in the medical management of diabetes?

QUESTION 1: HOW IS PPG DEFINED?
The word postprandial means after a meal; therefore, PPG concentrations refer to plasma glucose concentrations after eating. Many factors determine the PPG profile. In nondiabetic individuals, fasting plasma glucose concentrations (i.e., following an overnight 8- to 10-h fast) generally range from 70 to 110 mg/dl. Glucose concentrations begin to rise ~10 min after the start of a meal as a result of the absorption of dietary carbohydrates. The PPG profile is determined by carbohydrate absorption, insulin and glucagon secretion, and their coordinated effects on glucose metabolism in the liver and peripheral tissues.

The magnitude and time of the peak plasma glucose concentration depend on a variety of factors, including the timing, quantity, and composition of the meal. In nondiabetic individuals, plasma glucose concentrations peak ~60 min after the start of a meal, rarely exceed 140 mg/dl, and return to preprandial levels within 2–3 h. Even though glucose concentrations have returned to preprandial levels by 3 h, absorption of the ingested carbohydrate continues for at least 5–6 h after a meal.

Since people with type 1 diabetes have no endogenous insulin secretion, the time and height of peak insulin concentrations, and resultant glucose levels, are dependent on the amount, type, and route of insulin administration. In type 2 diabetic patients, peak insulin levels are delayed and are insufficient to control PPG excursions adequately. In type 1 and type 2 diabetic individuals, abnormalities in insulin and glucagon secretion, hepatic glucose uptake, suppression of hepatic glucose production, and peripheral glucose uptake contribute to higher and more prolonged PPG excursions than in nondiabetic individuals.

Because the absorption of food persists for 5–6 h after a meal in both diabetic and nondiabetic individuals, the optimal time to measure postprandial glucose concentration must be determined. Practical considerations limit the number of blood samples that can be obtained. In general, a measurement of plasma glucose 2 h after the start of a meal is practical, generally approximates the peak value in patients with diabetes, and provides a reasonable assessment of postprandial hyperglycemia. Specific clinical conditions, such as gestational diabetes or pregnancy complicated by diabetes, may benefit from testing at 1 h after the meal.

QUESTION 2: WHAT IS THE RELATIONSHIP AMONG PPG, FPG, AND HBA1C?
Hemoglobin A1c is a measure of the degree to which hemoglobin is glycosylated in erythrocytes and is expressed as a percentage of total hemoglobin concentration. It reflects the exposure of eryth-
correlation between HbA1c and MPG (indicator of long-term glycemic control. 776
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meal were indistinguishable (points, including mean preprandial or plasma glucose correlating less well. No
ences were detected in the relationship among HbA1c, FPG, and PPG were ana-
yzed in a 24-week randomized clinical trial involving three treatment groups (a rapid-acting insulin secretagogue, an insulin sensitizer, and a combination of both agents) and a placebo group. FPG was found to correlate best with HbA1c ($r \approx 0.62–0.67$), the correlation with PPG was weaker ($r \approx 0.22–0.56$) and was inconsistent across the three treatment and placebo groups. There was no significant correlation between HbA1c and PPG.
In summary, there are insufficient data to determine accurately the relative contribution of the FPG and PPG to HbA1c. It appears that FPG is somewhat better than PPG in predicting HbA1c, especially in type 2 diabetes.

**QUESTION 3: WHAT IS THE CONTRIBUTION OF PPG TO THE LONG-TERM COMPLICATIONS OF DIABETES?**

Controlled clinical trials, such as the DCCT (1) and the Stockholm Diabetes Study (3) in type 1 diabetes and the Ku-mamoto Study (4) and UKPDS (2) in type 2 diabetes, have established that therapies directed at achieving normal glycemia are effective in reducing the development and delaying the progression of long-term microvascular diabetic complications.

Even before these clinical trials were completed, observational studies demonstrated a positive association between retinopathy and hyperglycemia. The epidemiological studies relied predominantly on measures of chronic glycemia, such as HbA1c. In the relatively few studies in which HbA1c, FPG, and 2-h OGTT value were measured, all were similarly associated with the risk for retinopathy. Considering the interrelationships among these glyce-
mic measures (described in the previous section), these results are not surprising.

The interventional studies in type 1 diabetes aimed to lower glucose levels with the goal of maintaining HbA1c as close to the nondiabetic range as safely possible. In the DCCT, the primary focus of intensive therapy was to lower prepran-
dial (up to 1 h before meals) and bedtime self-monitored blood glucose levels. If HbA1c goals were not achieved, further
attention was focused on lowering the 90-
to 120-min postprandial levels. In type 2 diabetes, the UKPDS adjusted glucose-
lowering therapy to attain fasting glucose goals. Epidemiological analyses of the DCCT (5) and UKPDS (6) results rein-
force the relationship between chronic gly-
cremia, as measured by HbA1c, and risk for developing long-term complications. No clinical trial data address whether PPG, independent of other measures of glycemia, plays a unique role in the pathogenesis of diabetes-specific complications. Similarly, no clinical trial data outside of studies in gestational diabetes have exam-
ined the need to treat postprandial glucose levels specifically to prevent complications.

Interventional studies have not demonstr-
onstrated a convincing beneficial effect of glucose lowering on CVD outcomes (1, 2), and no clinical trials have examined whether treatments that primarily lower PPG decrease cardiovascular events. As-
ociations of CVD and CVD risk factors with glycemia have been demonstrated over a broad range of glucose tolerance, from normal to diabetic, in several epide-
miological studies. Whether the FPG or a postchallenge (OGTT) glucose level is an independent risk factor for CVD in these studies is controversial and requires fur-
ther study.

**QUESTION 4: UNDER WHAT CIRCUMSTANCES SHOULD PEOPLE WITH DIABETES BE TESTED FOR PPG?**
The only setting in which PPG monitoring has been shown to improve outcomes is gestational diabetes. In one study, women with gestational diabetes were randomly assigned either to a treatment program in which therapy was adjusted to achieve predefined FPG and PPG levels or to one targeting premeal and bedtime glucose levels (7). The women assigned to postprandial monitoring achieved a lower HbA1c and required fewer Caesarian sec-
tions for cephalopelvic disproportion, and their babies suffered less frequently from macrosomia and neonatal hypogly-
cemia. Whether similar outcomes could have been achieved with premeal moni-
toring if lower premeal targets had been selected is unknown. There are no com-
parable randomized clinical studies in people with type 1 or type 2 diabetes exam-
ining whether PPG monitoring im-
proves outcomes.

Are there other clinical situations in
which PPG monitoring should be considered part of the overall treatment plan? There are no adequate randomized clinical trial data to answer this question, but the following are clinical situations in which PPG monitoring could be considered:

A. Suspected postprandial hyperglycemia. In patients who achieve their premeal glucose targets, but whose overall glycemic control as determined by HbA1c is inappropriately high, PPG monitoring and therapy to minimize PPGEs may be beneficial.

B. Monitoring treatment aimed specifically at lowering PPG. In patients with type 1 or type 2 diabetes who are treated with glucose-lowering agents expected primarily to reduce PPG, monitoring may be useful in titrating these treatments or in confirming that patients have responded to the intervention. It is also possible that PPG monitoring may be beneficial to evaluate the effect of changes in nutrition or exercise patterns.

C. Hypoglycemia. Hypoglycemia in the postprandial period is rare except in response to exercise or rapid-acting insulin analogs.

There are insufficient data either to support or to refute the need for extensive or routine PPG monitoring in diabetes, except in the setting of pregnancy. Since self-monitoring of blood glucose represents a significant financial and personal burden for patients, decisions regarding PPG monitoring should be based on the needs and responses of individual patients. The decision to recommend a glucose monitoring plan should be made judiciously, accompanied with specific patient education, and reviewed and modified regularly by the health care team.

**QUESTION 5: WHAT ARE THE BENEFITS AND RISKS OF SPECIFICALLY LOWERING PPG IN AN EFFORT TO ACHIEVE BETTER GLYCEMIC CONTROL?**

Randomized clinical trials have demonstrated that a reduction in the long-term complications of diabetes is proportional to average glycemia as determined by HbA1c. However, it is unclear whether reducing PPG provides additional improvements in HbA1c.

What, if any, are the documented benefits of specifically lowering PPG? The definitive answer to this question can only come from well-designed, randomized, controlled clinical trials. The availability of oral agents and insulin analogs that specifically target postprandial glucose levels has provided tools to perform such studies.

Alpha-glucosidase inhibitors, rapidly-acting oral insulin secretagogues, and rapid-acting insulin analogs predominantly lower PPG. They also reduce HbA1c. It is unclear, however, to what extent HbA1c is lowered by these drugs because of their effects on PPG as compared with their effects on FPG. Furthermore, it is not clear whether therapies that target PPG provide unique benefits relative to other pharmacological therapies that lower HbA1c comparably. Performing such studies will be important.

It has been suggested that agents that specifically lower PPG may decrease the risk of hypoglycemia and weight gain. These claims have not been consistently supported by randomized, controlled studies. There appear to be no unique risks associated with the specific lowering of PPG to achieve HbA1c goals.

**QUESTIONS 6: WHAT ADDITIONAL RESEARCH NEEDS TO BE PERFORMED TO CLARIFY THE ROLE OF PPG IN THE MEDICAL MANAGEMENT OF DIABETES?**

There are several issues that should be considered when designing studies to examine PPG. Studies should be performed in well-defined patient groups; at a minimum, separation of patients by type of diabetes is necessary. It is also quite likely that results of studies in patients with impaired fasting glucose and/or impaired glucose tolerance may be different from those in patients with type 2 diabetes and different degrees of fasting hyperglycemia. In particular, elderly patients, in whom postprandial hyperglycemia may be the most prevalent abnormality in glucose homeostasis, may warrant special attention. In studies of the impact of PPG on diabetic complications, it is important to differentiate between microangiopathy and macroangiopathy as end points. Finally, attention must be paid to differences in therapeutic programs (e.g., nutrition therapy versus oral antihyperglycemic agents versus insulin) and type of oral glucose-lowering drugs used. Given these general principles, the following specific questions should be addressed:

A. How do we best assess postprandial hyperglycemia and the relationships among FPG, PPG, and HbA1c? The term postprandial hyperglycemia is used very loosely because its assessment has not been standardized. Some of the most obvious unresolved issues related to the definition of PPG include: 1) use of a carefully defined meal test versus the OGTT; 2) variations in size and macronutrient content of test meals; 3) timing of blood sampling after standard meals or glucose challenge; and 4) how often any of these measurements should be made in order to provide meaningful information. Resolving these issues, in the appropriate experimental setting, will provide information to define more precisely the nature of the relationships among FPG, PPG, and HbA1c. This information is also necessary to address broader issues, such as the relative importance of PPG and FPG in assessing glycemic control and/or predicting the risk for diabetic complications.

B. What is the clinical utility of using measurements of PPG to improve glycemic control? At present, HbA1c measurements are the “gold standard” for assessing long-term glycemic control. The fundamental question to be answered is whether measuring premeal glucose, FPG, or PPG, alone or in combination, will be most helpful in adjusting treatment to achieve HbA1c goals while minimizing hypoglycemia. Although useful insights concerning these issues have been gained from retrospective analyses, definitive answers require intervention studies. These studies should determine whether treatments aimed at controlling FPG and PPG result in lower HbA1c than do treatments that predominantly affect FPG and/or premeal glucose levels.

C. In the presence of equivalent HbA1c values, does an excessive rise in PPG uniquely affect chronic diabetic complications? It is unclear whether excessive excursions of PPG have a significant impact on the development of diabetic microvascular or macrovascular complications independent of...
HbA1c levels. To address this fundamental question, studies must be designed to control FPG versus PPG levels while aiming to achieve similar and acceptable HbA1c levels.

Because CVD is the major cause of morbidity and mortality in patients with diabetes, and in type 2 diabetes in particular, understanding the impact on CVD events of treatments directed at specifically lowering PPG is crucial. Furthermore, the relationship between PPG excursions and both the well-established risk factors and the more recently identified putative mechanisms for CVD should be examined.

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APPENDIX

Consensus Panel
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Speakers at the Conference
Paul J. Beisswenger, MD; Antonio Ceriello, MD; William C. Duckworth, MD; William C. Knowler, MD, DrPH; James B. Meigs, MD, MPH; Michele Muggeo, MD; and F. John Service, MD, PhD.

Oral Abstract Presenters at the Conference
Enzo Bonora, MD, PhD; Frederick L. Brancati, MD; Michael M. Engelgau, MD; Thomas Erlinger, MD, MPH; David E. Goldstein, MD; Francine Ratner Kaufman, MD; M. Sue Kirkman, MD; Elizabeth Koller, MD; Romano Nosadini, MD; and Thomas M.S. Wolever, MD, PhD.

References
5. The Diabetes Control and Complications Trial Research Group: The relationship of glycemic exposure (HbA1c) to the risk of development and progression of retinopathy in the Diabetes Control and Complications Trial. Diabetes 44:968–983, 1995