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# Starch chemistry affects kinetics of glucose absorption and insulin response in swine ☆

P.R. Regmi [a], J.J. Matte [b], T.A.T.G. van Kempen [c,d], R.T. Zijlstra [a,*]

[a] University of Alberta, Edmonton, AB, Canada
[b] Agriculture and Agri-Food Canada, Sherbrooke, QC, Canada
[c] Provimi Research and Innovation Centre, Brussels, Belgium
[d] North Carolina State University, Raleigh, NC, USA

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ABSTRACT

Starch chemistry may affect kinetics of nutrient absorption and insulin secretion. The objective was to define the glucose absorption kinetics and insulin response in swine to diets containing starch with a wide range in chemistry and *in vitro* digestion patterns. Diets tested contained purified starch (700 g/kg diet) ranging from rapid to slow digestible starch [maximal rate of *in vitro* glucose release (%)/min: 1.53, rapid; 0.94, moderate rapid; 0.37, moderate slow; and 0.14, slow]. *In vitro* rate of starch digestion was characterized using an assay modified after Englyst et al. (2003). *In vivo* kinetics were determined using four pigs (35.0 ± 0.2 kg) surgically fitted with catheters in the portal vein and carotid artery and a portal blood flow probe. Pigs were fed for 7-d periods in a 4 × 4 Latin square. On d 7, blood was collected for 12 h postprandially. Net glucose absorption differed ($P<0.05$) among diets at 45, 90, 120, and 150 min postprandial. Cumulative glucose absorption up to 12 h did not differ among rapid, moderate rapid, and moderate slow digestible starch diets, but these diets had a higher ($P<0.05$) cumulative glucose absorption than slow digestible starch diets. In addition, portal plasma insulin and C-peptide release peaked at 30 min postprandial and differed ($P<0.05$) among diets at 30 and 60 min postprandial, except between moderate rapid and moderate slow digestible starch diets. In conclusion, starches with a wide difference in *in vitro* starch digestion affect kinetics of glucose absorption and insulin response in swine.



## 1. Introduction

Starch is the major dietary source of glucose for monogastric species. Reduced postprandial glucose and insulin response is beneficial for management of diseases related to carbohydrate metabolism such as type-II diabetes (Ells et al., 2005) and may affect feed intake and feed efficiency in pigs (van Kempen et al., 2007). An important factor affecting glucose absorption and consequent insulin responses is starch chemistry. For instance, consumption of diets containing slow digestible starch (SDS) and resistant starch (RS) can decrease postprandial plasma glucose and insulin (Ells et al., 2005) because of reduced kinetics of starch digestion (Morand et al., 1992). However, the effect of SDS and RS on glucose and insulin response may not be observed when the range of digestibility is not sufficiently wide (Noah et al., 2000). Therefore, pure starches with a wide range in amylose content were used to test the hypothesis that diets high in SDS content reduce peak and cumulative glucose absorption and insulin response. The objective of the study was to define the glucose absorption kinetics and insulin response in swine to diets containing starch with a wide range in chemistry and *in vitro* digestion patterns.

## 2. Materials and methods

### 2.1. Animal experiment and sample analyses

The animal protocol was approved by the Animal Care and Use Committee for Livestock at the University of Alberta. Four

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* Corresponding author. Tel.: +1 780 492 8593; fax: +1 780 492 4265.
*E-mail address:* ruurd.zijlstra@ualberta.ca (R.T. Zijlstra).

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female pigs (35.0 ± 0.2 kg BW) catheterized in the portal vein and carotid artery and a flow probe was installed around the portal vein (Hooda et al., 2009). Pigs were fed one of four diets containing purified starches (700 g/kg diet) in a 4×4 Latin square design. Diets also contained casein, fishmeal, cellulose, and canola oil. Pigs were fed 1200 g/d in two equal meals at 0800 and 2000. On d 7 of each period, blood was collected every 15 min from the portal vein and carotid artery from −15 to 60 min, then every 30 min until 240 min, every 60 min until 480 min, and 600 min and 720 min after feeding. During each collection, portal blood flow rate was measured using a flowmeter (Transonic Systems Inc., Ithaca, NY, USA). Plasma flow rate was calculated from blood flow using the equation; plasma flow = blood flow × (1 − hematocrit). Plasma was analyzed for glucose (glucose oxidase kits; Diagnostics Chemicals Ltd., Charlottetown, PEI, Canada) and insulin and C-peptide (RIA kits; Linco, St. Louis, MO, USA).

### 2.2. Starch characteristics

Remyline AX-DR rice starch, Remy B7 rice starch (Remy Industries, Leuven-Wijgmaal, Belgium), Nastar pea starch (Cosucra Group Warconing, Warconing, Belgium), and Gelose 80 corn starch (Penford Food Ingredients, Centennial, CO, USA) were used. The *in vitro* digestibility of the starch samples were determined with an assay modified after Englyst et al. (2003) based on porcine pancreatin (van Kempen et al., 2007). Starches were considered rapid, moderate rapid, moderate slow, and slow digestible based on the maximal rate of glucose release (%/min) (1.53, 0.94, 0.37, and 0.14, respectively). Starch sources had a wide range in SDS (starch digested from 20 to 120 min *in vitro*) and RS contents (starch undigested after 120 min *in vitro*) (rapid; 68.1 and 3.1%; moderate rapid, 46.8 and 33.5%; moderate slow, 31.7 and 61.2%; and slow digestible starch, 11.4 and 85.0%, respectively).

### 2.3. Calculation and statistical analysis

Net glucose absorption and C-peptide production was calculated using the formula $q = (Cp - Ca)F(dt)$. Cumulative glucose absorption was calculated subsequently using the formula $Q = \sum_{t_0}^{t_n} q$ (Rérat et al., 1984).

Where; $q$ = amount of nutrient absorbed or hormone released within time period $dt$; $Cp$ and $Ca$ = concentration of analytes in portal and arterial plasma, respectively; $F$ = plasma flow in the portal vein; and $Q$ = amount of analyte absorbed from time $t_0$ to $t_n$. Glucose absorption, plasma insulin and C-peptide release were analyzed using repeated measures (version 9.1; SAS Inst. Inc., Cary, NC, USA) in a mixed model that included diet, time and their interaction as fixed effects and pig and period as random effects.

## 3. Results

Net glucose absorption differed most pronouncedly between 45 and 150 min postprandial (Fig. 1 A); rapid digestible starch had a higher ($P<0.05$) glucose absorption than slow, moderate slow, and moderate rapid digestible starch. Net glucose absorption was negative at 8 and 12 h in rapid digestible starch

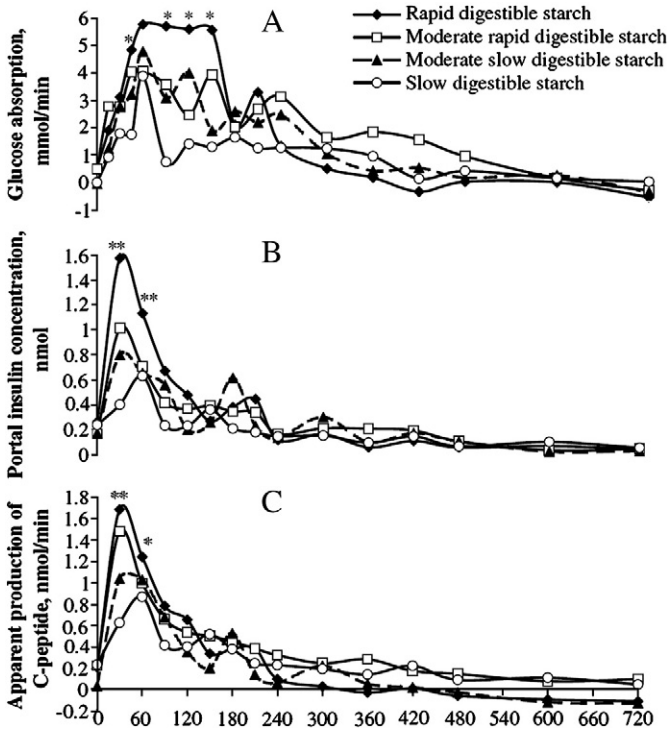


**Fig. 1.** Effect of diets containing starches with varying digestibility on postprandial glucose, insulin and C-peptide response; A, Glucose absorption; B, Portal insulin concentration; C, C-peptide release; *$P<0.05$; **$P<0.01$; SEM was omitted for clarity.

**Table 1**
Effect of diets containing starches with varying digestibility on cumulative glucose absorption (% of starch consumed) at specific time points postprandial.

| Time after feeding, h | Rapid digestible starch | Moderate rapid digestible starch | Moderate slow digestible starch | Slow digestible starch | Pooled SEM | *P*-value |
|---|---|---|---|---|---|---|
| 1 | 10.1 | 9.0 | 7.9 | 6.3 | 1.60 | 0.71 |
| 2 | 24.6 [a] | 17.4 [a] | 17.2 [a] | 9.5 [b] | 2.78 | <0.0001 |
| 4 | 40.4 [a] | 32.4 [ab] | 29.3 [b] | 17.7 [c] | 4.47 | <0.0001 |
| 6 | 42.1 [a] | 41.7 [ab] | 33.2 [b] | 24.3 [c] | 4.37 | <0.0001 |
| 8 | 41.3 [ab] | 48.2 [a] | 35.1 [b] | 26.0 [c] | 5.94 | <0.0001 |
| 12 | 38.7 [a] | 47.5 [a] | 38.9 [a] | 27.2 [b] | 7.04 | <0.0001 |

[a–c] Within a row, means without a common superscript differ ($P<0.05$).

and at 12 h in moderate rapid and moderate slow digestible starch diets. Cumulative glucose absorption up to 1 h postprandial did not differ significantly among starch sources (Table 1). By 2 h postprandial, cumulative glucose uptake was 2.5 times higher ($P<0.01$) for rapid vs. slow digestible starch. However, by 12 h, cumulative glucose absorption was lower ($P<0.05$) only for slow digestible starch. The ranking of starches was consistent from rapid to slow digestible starch. Portal insulin concentration and C-peptide release peaked at 30 min postprandial and differed ($P<0.05$) among starch sources at 30 and 60 min postprandial (Fig. 1B and C).

## 4. Discussion

Kinetics of glucose absorption and insulin secretion differed greatly among starch sources. Pure starches were selected so that observed effects could be related to starch chemistry without confounding effects of protein matrix, NSP, or other compounds. C-peptide release is a reliable indicator of pancreatic insulin response, because insulin and C-peptide are released in equimolar amounts but unlike insulin, the hepatic and prehepatic extraction of C-peptide is negligible (Guan et al., 2000).

An increased rate of glucose uptake in pigs was expected for rapid digested starch, based on *in vitro* digestibility data, and indicates that gastric emptying did not confound the ranking of starch sources. Negative net glucose absorption after 8 h postprandial in rapid digestible starch reflects an intestinal utilization of systemic glucose. In the systemic circulation, starch chemistry causes differences in plasma glucose and insulin response after a meal (Deng et al., 2010), and our research indicates that this change is directly caused by difference in kinetics of glucose absorption. A wide range in starch chemistry was required to detect the difference in responses (this study; Behall and Hallfrisch, 2002). By 3 h postprandial, a 3-fold increase in glucose uptake for rapid vs. slow digestible starch coincided with increased insulin secretion for rapid digestible starch, whereas differences were smaller by 12 h. Therefore, difference in feed intake and feed efficiency observed among pigs fed starch sources differing in rate of glucose release (Van Kempen et al., 2007) might be partially modulated by insulin.

In conclusion, starch with slower rate of *in vitro* digestion reduced peak glucose absorption and insulin release *in vivo*, while less affecting cumulative glucose absorption. The rate of starch digestion is thus an important modifier of the metabolic response to a starch source with implications for voluntary food intake, adiposity, and potentially health. Further studies are required to understand the link between starch chemistry and enteric hormone secretion and flow of other dietary nutrients and metabolites from enteric fermentation.

## Conflict of Interest

None of the authors has a conflict of interest.

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