Comparative effects of oral and intraduodenal glucose on blood pressure, heart rate, and splanchnic blood flow in healthy older subjects

Diana Gentilcore, Nivasinee S. Nair, Lora Vanis, Christopher K. Rayner, James H. Meyer, Trygve Hausken, Michael Horowitz, and Karen L. Jones

1Discipline of Medicine, University of Adelaide, Royal Adelaide Hospital, and 2National Health and Medical Research Council of Australia Centre of Clinical Research Excellence in Nutritional Physiology, Interventions and Outcomes, Adelaide, South Australia, Australia; and 3Institute of Medicine, University of Bergen and 4National Centre for Ultrasound in Gastroenterology, Haukeland University Hospital, Bergen, Norway

Submitted 20 April 2009; accepted in final form 22 June 2009

Postprandial hypotension, defined as a decrease in systolic blood pressure ≥20 mmHg, occurring within 2 h of the end of a meal (23, 25, 38, 39), is an important clinical problem, most commonly affecting the elderly and patients with autonomic dysfunction, the latter often secondary to diabetes (23, 25, 38, 39). Postprandial hypotension is associated with significant complications, including syncope and falls (25) and, in some cases, stroke and angina (1, 25, 51).

The stomach is likely to modulate the hypotensive response to a high-carbohydrate meal in two ways, first, by controlling the rate at which glucose enters the small intestine. Our laboratory’s studies in healthy older subjects (26, 42) and patients with type 2 diabetes (28, 46) have established that there is a direct relationship between the magnitude of the fall in systolic blood pressure with the rate of small intestinal delivery of glucose (26, 28, 41, 42), a response that depends on the total load of glucose entering the duodenum independent of glucose concentration (11, 27). When glucose enters the small intestine, it inhibits gastric emptying in a load-dependent fashion, so that glucose entry is sustained at ~3 kcal/min (21, 22). Second, the stomach may reduce the hypotensive response induced by the ingestion of carbohydrate via a “gastrovascular reflex” triggered by gastric distension. For example, in healthy older subjects, following ingestion of glucose drinks of varying volumes and concentrations, the rate of duodenal entries of glucose was similar, but the meals of larger volume were associated with decreased falls in blood pressure (27). The minimum gastric volume needed to produce this mitigation is poorly established; however, using two-dimensional (2D) ultrasonography to monitor gastric volumes, our laboratory has recently estimated that 300 ml or less of a meal in the stomach may suffice (14).

Since gastric distension appears to attenuate the effects of duodenal glucose on blood pressure (14, 27), it may also modulate the splanchnic blood flow response to enteral glucose. The role of gastric distension in the regulation of splanchnic blood flow has not yet been evaluated. The aims of this present study were twofold. First, to extend our previous observation of intragastric meal volume modulating the hypotensive response to duodenal glucose, we compared the hypotensive response to glucose as it spontaneously emptied from the stomach on “day 1” to the hypotensive response of glucose infused directly into the duodenum at the rate that mimicked spontaneous gastric emptying on “day 2”. On the first day, intragastric volumes were monitored continuously using three-dimensional (3D) ultrasonography, a new method that has been recently validated as an accurate measure of gastric volume/gastric emptying in both healthy young subjects (12) and patients with diabetic gastroparesis (48). Second, on both days, superior mesenteric artery flow was measured to determine whether gastric distension, induced by the oral glucose load, on day 1 resulted in a reduced flow compared with day 2. We postulated that the hypotensive effect after oral glucose would be less than after duodenal glucose because of the gastrovascular reflex, and that this difference may be reflected in reduced superior mesenteric artery flow.
**MATERIALS AND METHODS**

**Subjects**

Eight healthy older subjects (five men and three women), with a median age of 71 yr (range: 66–75 yr) and body mass index of 23.3 kg/m² (range: 20.3–27.0 kg/m²), recruited by advertisement, were studied. We calculated that a minimum of five subjects would be required to detect a mean difference in systolic blood pressure of \( \sim 13 \) mmHg, with power of 0.80, assuming a significance value \( < 0.05 \) (56). All subjects were nonsmokers. None had a history of gastrointestinal disease or surgery; diabetes; significant respiratory, renal, hepatic, or cardiac disease; chronic alcohol abuse or epilepsy; or were taking medication known to influence blood pressure or gastrointestinal function. All of the eight subjects had participated previously in research studies involving intubation.

The protocol was approved by the Human Research Ethics Committee of the Royal Adelaide Hospital, and each subject provided written, informed consent before their involvement. All experiments were carried out in accordance with the Declaration of Helsinki.

**Protocol**

Each subject was studied on two occasions, separated by 3–29 days. On each day, subjects attended the University of Adelaide, Discipline of Medicine, at the Royal Adelaide Hospital at 0830, following an overnight fast (10.5 h for solids; 8.5 h for liquids) (11, 13, 14). On the first day (day 1), on arrival, an intravenous cannula was placed in a left antecubital vein for blood sampling, and an automated blood pressure cuff was positioned around the right arm for measurement of blood pressure and heart rate (11, 13, 14). Each subject was then allowed to rest comfortably in the recumbent position for \( \sim 30 \) min. At time \( t = -2 \) min, the subject was seated in a chair and consumed a drink comprising 75 g glucose monohydrate dissolved in water, with a total volume of 300 ml (255 kcal). The rate of gastric emptying, blood pressure (systolic and diastolic), heart rate, and superior mesenteric artery flow were then measured for 120 min. On the second day (day 2), following placement of the intravenous cannula, a silicone-rubber catheter (external diameter \( \sim 4 \) mm) (Dentsleeve International, Mii Scientific, Mississauga, Canada) was introduced into the stomach via an anesthetized nostril (11, 13, 14). The assembly included an infusion channel (internal diameter \( \sim 1 \) mm) and was positioned so that the infusion port was located \( \sim 10 \) cm distal to the pylorus (i.e., in the duodenum), as well as two other channels that were positioned in the antrum (2.5 cm proximal to the pylorus) and duodenum (2.5 cm distal to the pylorus), respectively, and were perfused with 0.9% saline. The correct positioning of the catheter was maintained by continuous measurement of the transmucosal potential difference between the antral (\( \sim 40 \) mV) and the duodenal (0 mV) channel (11, 13, 14). For this purpose, an intravenous cannula filled with sterile saline was placed subcutaneously in the left forearm and used as a reference electrode (11, 13, 14). The tip of the catheter passed into the duodenum by peristalsis, which took \( \sim 30 \) min. At time \( t = 0 \) min, the subject was seated in a chair and consumed a drink comprising 75 g glucose monohydrate dissolved in water, with a total volume of 300 ml (255 kcal). The rate of gastric emptying, blood pressure (systolic and diastolic), heart rate, and superior mesenteric artery flow were then measured for 120 min. On the second day (day 2), following placement of the intravenous cannula, a silicone-rubber catheter (external diameter \( \sim 4 \) mm) (Dentsleeve International, Mii Scientific, Mississauga, Canada) was introduced into the stomach via an anesthetized nostril (11, 13, 14). The assembly included an infusion channel (internal diameter \( \sim 1 \) mm) and was positioned so that the infusion port was located \( \sim 10 \) cm distal to the pylorus (i.e., in the duodenum), as well as two other channels that were positioned in the antrum (2.5 cm proximal to the pylorus) and duodenum (2.5 cm distal to the pylorus), respectively, and were perfused with 0.9% saline. The correct positioning of the catheter was maintained by continuous measurement of the transmucosal potential difference between the antral (\( \sim 40 \) mV) and the duodenal (0 mV) channel (11, 13, 14). For this purpose, an intravenous cannula filled with sterile saline was placed subcutaneously in the left forearm and used as a reference electrode (11, 13, 14). The tip of the catheter passed into the duodenum by peristalsis, which took between 20 and 120 min. An automated blood pressure cuff was placed around the right arm (11, 13, 14). Once intubated, the subject rested in the recumbent position. Approximately 30 min after the tube was positioned correctly (at \( t = 0 \) min), the subject received an intraduodenal infusion of glucose for 120 min. The energy delivery (kcal/min) of the intraduodenal infusion was determined by visually drawing lines of best fit for each of the individual gastric-emptying curves generated on day 1, i.e., the rate of nutrient delivery during the intraduodenal infusion mimicked that observed after the oral glucose load (Fig. 1). In some cases, the rate of energy delivery varied over time and was not linear for the total 120 min, e.g., gastric emptying was clearly initially more rapid in some subjects than slowed. Intraduodenal infusions were performed using a volumetric infusion pump (Gemini PC-1; IMED Corp, San Diego, CA), and the energy delivery of the infusion was regulated as per the predetermined infusion rates. Blood pressure (systolic and diastolic), heart rate, and superior mesenteric artery flow were measured for 120 min. At \( t = 120 \) min, the catheter was removed. On 1 day, cardiovascular autonomic nerve function was evaluated immediately after the completion of the study (9, 44). On both study days, subjects were given a light meal before leaving the laboratory.

**Measurements**

**Gastric emptying.** Ultrasonography measurements were performed using a Logiq 9 ultrasonography system (GE Healthcare Technologies, Sydney, Australia) with TruScan Architecture (i.e., built-in magnetically sensed 3D), as described previously (12). For 3D positioning and orientation measurement (POM), a transmitter was placed close to the subject, and a snap-on sensor was attached to a 3.5C broad spectrum 2.5- to 4-MHz convex transducer (12, 49). As the transmitter produces a spatially varying magnetic field, and ferrous and conductive metals distort the magnetic field, all metal objects were removed from the subject and from the area directly between the POM transmitter and sensor (32). The POM transmitter was placed behind (\( \sim 10 \) cm) the subject (16), at the level of the stomach, so that the subject was positioned between the ultrasonography scanner and the transmitter. For 3D data acquisition, the subject was scanned at \( t = -2 \) min, \( t = 0 \) min (i.e., immediately following ingestion of the drink), and then at 15-min intervals between \( t = 0 \) and 120 min. Regions of interest were drawn around the total stomach, and the volume of the drink in the total stomach was derived and expressed as a percentage of the original volume at \( t = 0 \) min in the total stomach (i.e., 100%) (12). Gastric emptying curves (expressed as percent retention over time) were derived for the total stomach at 0, 15, 30, 45, 60, 75, 90, 105, and 120 min.

**Blood pressure and heart rate.** Blood pressure (systolic and diastolic) and heart rate were measured using an automated oscillometric blood pressure monitor (DINAMAP ProCare 100, GE Medical Systems, Milwaukee, WI) at \( t = -9, -6 \), and \( -3 \) min before both ingestion of the drink and commencement of the intraduodenal infusion, and then every 3 min between \( t = 0 \) and 120 min (11). “Baseline” blood pressure and heart rate, i.e., \( t = 0 \) min, were calculated as the mean of measurements taken at \( t = -9, -6 \), and \( -3 \) min before ingestion of the drink and commencement of the intraduodenal infusion. Postprandial hypotension was defined as a fall in systolic blood pressure of \( \geq 20 \) mmHg that was sustained for at least 30 min (25).

**Superior mesenteric artery flow.** Superior mesenteric artery flow was measured by Duplex ultrasonography (i.e., B-mode and Doppler imaging) using a Logiq 9 ultrasonography system (GE Healthcare Technologies, Sydney, Australia), as described previously (43). Each subject was scanned using a 3.5C broad spectrum 2.5- to 4-MHz convex transducer (13, 43) at \( t = -2, 5, \) and 10 min and then at 15-min intervals between \( t = 0 \) and 120 min. Blood flow (ml/min) was
calculated immediately using the formula: $\pi \times r^2 \times \text{TAMV} \times 60$, where $r$ is the radius of the superior mesenteric artery, and TAMV is the time-averaged mean velocity (43).

**Blood glucose concentrations.** Venous blood samples (~2 ml) were obtained before both ingestion of the drink and the commencement of the intraduodenal infusion (i.e., $t = -2$ min) and at 15-min intervals between $t = 0$ and 120 min (11). Blood glucose concentrations were determined immediately using a portable blood glucose meter (Medisense Precision Q-1-D System, Abbott Laboratories, Medisense Products, Bedford, MA) (11).

**Autonomic function.** Autonomic nerve function was assessed using standardized cardiovascular reflex tests (9, 44). Parasympathetic function was evaluated by the variation (R-R interval) of the heart rate during deep breathing and the heart rate response to standing (30:15 ratio). Sympathetic function was assessed by the fall in systolic blood pressure in response to standing. Each of the test results was scored according to age-adjusted predefined criteria as 0 = normal, 1 = borderline, and 2 = abnormal for a total maximum score of 6. A score ≥ 3 was considered to indicate autonomic dysfunction (9, 44).

**Statistical analysis.** Data were evaluated using repeated-measures two-way ANOVA, with “treatment” and “time” as within-subject factors. Systolic and diastolic blood pressure and heart rate were analyzed as changes from baseline. Superior mesenteric artery flow, blood glucose concentrations, and duodenal entry of glucose were analyzed as absolute values. Data were analyzed from $t = -2$ to 120 min to determine the effects (treatment and time) of oral and intraduodenal glucose. One-way ANOVA was used to analyze the effects of time on systolic and diastolic blood pressure, heart rate, superior mesenteric artery flow, and blood glucose. In all analyses, post hoc comparisons of adjusted means were performed using Student’s $t$-tests. The maximum fall in systolic blood pressure and rise in heart rate were defined as the greatest mean changes from baseline in each subject at any given time point for each treatment. All analyses were performed using Statview (version 5.0; Abacus Concepts, Berkeley, CA) and SuperANOVA (version 1.11, Abacus Concepts). Data are presented as mean values ± SE. A $P$ value < 0.05 was considered significant in all analyses.

**RESULTS**

The studies were well tolerated. One subject reported diarrhea after completion of the intraduodenal glucose infusion. In this subject, the magnitude of the fall in systolic blood pressure was comparable to the remainder of the group. Data for this subject were, accordingly, included in the analysis. No subject had definite autonomic neuropathy; median score 0.6 (range: 0–2). While no subject experienced postprandial hypotension (i.e., a fall in systolic blood pressure >20 mmHg sustained for at least 30 min), in two the magnitude of the fall in systolic blood pressure was ≥20 mmHg: one after oral glucose, and one during intraduodenal glucose infusion. The number of infusion rates on day 2, calculated by drawing lines of best fit on the gastric emptying curves, per individual, varied between 1 and 4. The total amount of glucose infused on day 2 ranged from 99 to 258 ml, i.e., 84–219 kcal (Fig. 1).

**Gastric Emptying**

See Fig. 1. The average gastric emptying rate on day 1 for the total 120 min was 1.3 ± 0.1 kcal/min (range: 0.7–1.8 kcal/min). The amount of glucose remaining in the stomach at 120 min varied from 42 to 201 ml (mean 115.9 ± 19.0 ml), i.e., 36–171 kcal (mean ~98.6 kcal).

**Baseline Blood Pressure and Heart Rate**

There was no significant difference in baseline (i.e., $t = 0$ min) blood pressure or heart rate between the 2 days (oral glucose vs. intraduodenal glucose infusion): systolic blood pressure (124.0 ± 5.8 vs. 127.6 ± 7.2 mmHg; $P = 0.16$), diastolic blood pressure (74.0 ± 2.9 vs. 74.5 ± 3.5 mmHg; $P = 0.71$), and heart rate (63.8 ± 0.9 vs. 62.6 ± 1.6 beats/min; $P = 0.40$).

**Systolic blood pressure.** See Fig. 2A. There was a significant “treatment × time” effect for systolic blood pressure ($P = 0.01$) between the study days. Between $t = 0$ and 120 min, there was no significant fall in systolic blood pressure after oral glucose ($P = 0.22$); however, between $t = 60$ and 90 min, systolic blood pressure was less than baseline during intraduo-

---

Fig. 2. Changes ($\Delta$) in systolic blood pressure (A), diastolic blood pressure (B), and heart rate (C) from baseline in eight healthy older subjects in response to oral (○) and ID (●) glucose. Values are means ± SE. *$P < 0.01$; **$P < 0.001$. 

AJR-Regul Integr Comp Physiol • VOL 297 • SEPTEMBER 2009 • www.ajpregu.org
renal glucose infusion ($P < 0.05$). Systolic blood pressure was greater ($P < 0.01$) between $t = 60$ and 120 min after oral, compared with intraduodenal, glucose. At $t = 120$ min, there was no significant difference in systolic blood pressure from baseline after oral ($P = 0.19$) or intraduodenal ($P = 0.20$) glucose.

Diastolic blood pressure. See Fig. 2B. There was no significant difference in diastolic blood pressure between the 2 days ($P = 0.15$). Between $t = 0$ and 120 min, there was a fall in diastolic blood pressure after both oral ($P < 0.01$) and intraduodenal ($P < 0.001$) glucose. At $t = 120$ min, diastolic blood pressure was significantly lower than baseline after both oral ($P = 0.01$) and intraduodenal ($P = 0.04$) glucose.

Heart rate. See Fig. 2C. There was a trend for a treatment $\times$ time effect for heart rate ($P = 0.06$). Between $t = 0$ and 120 min, there was no significant change in heart rate after oral glucose ($P = 0.77$); however, there was an overall rise during intraduodenal glucose infusion between $t = 45$ and 75 min ($P < 0.05$). The maximum increase in heart rate after oral (9.6 $\pm$ 1.8 beats/min) and intraduodenal (10.9 $\pm$ 2.2 beats/min) glucose were not significantly different ($P = 0.73$). At $t = 120$ min, heart rate was not significantly different from baseline after oral ($P = 0.89$), but was greater than baseline after intraduodenal ($P = 0.05$), glucose.

Superior Mesenteric Artery Flow

See Fig. 3. There was no difference in baseline (i.e., $t = -2$ min) superior mesenteric artery flow between the two days (oral glucose vs. intraduodenal glucose: 826.3 $\pm$ 77.7 vs. 728.5 $\pm$ 52.5 ml/min; $P = 0.18$). There was a significant treatment $\times$ time effect ($P = 0.0001$) for superior mesenteric artery flow. Between $t = -2$ and 120 min, there was a rapid rise ($P < 0.0001$) in superior mesenteric artery flow following oral glucose, which was evident from $t = 5$ min ($P = 0.002$), and then a fall from approximately $t = 30$ min ($P = 0.0001$). Superior mesenteric artery flow also rose, albeit less, during intraduodenal glucose infusion ($P < 0.001$), and this was significant from $t = 45$ min ($P = 0.001$). Between $t = 5$ and 60 min, superior mesenteric artery flow was greater after oral ($P < 0.05$), compared with intraduodenal, glucose. At $t = 120$ min, superior mesenteric artery flow was greater than baseline after both oral ($P = 0.02$) and intraduodenal ($P = 0.04$) glucose.

Blood Glucose Concentrations

See Fig. 4. There was a significant difference in baseline (i.e., $t = -2$ min) blood glucose concentrations between the 2 days (oral glucose vs. intraduodenal glucose: 5.8 $\pm$ 0.21 vs. 6.2 $\pm$ 0.19 mmol/l; $P = 0.03$). There was a significant treatment $\times$ time effect ($P = 0.0001$) for blood glucose concentrations. Between $t = -2$ and 120 min, there was a rise in blood glucose concentrations from baseline on both days ($P < 0.0001$ for both), which was significant from $t = 15$ min following oral ($P = 0.0003$), and from $t = 45$ min during intraduodenal ($P = 0.0002$), glucose. Between $t = 15$ and 45 min, blood glucose concentrations were greater ($P < 0.01$) after oral compared with intraduodenal glucose. At $t = 120$ min, blood glucose concentrations were greater than at baseline after both oral and intraduodenal ($P = 0.01$ for both) glucose.

DISCUSSION

This study establishes that, in healthy older subjects, the magnitude of the systolic blood pressure response to an oral glucose load is substantially less, and superior mesenteric artery flow greater, compared with intraduodenal glucose infusion at a comparable rate.

Our laboratory’s previous studies (26, 28, 41, 46) have established that the rate of gastric emptying is an important determinant of the postprandial fall in blood pressure. In healthy older subjects, when glucose is infused intraduodenally at a rate of 3 kcal/min, the magnitude of the maximum fall in systolic blood pressure (mean $\pm$ 24 mmHg) is substantially greater compared with infusion at a rate of 1 kcal/min (mean $\pm$ 9 mmHg) (41). While our laboratory has shown that both oral (10, 15, 26–28, 46, 56) and enteral glucose (11, 13, 14, 41, 42) decrease blood pressure, the magnitude of the fall in blood pressure is less after oral compared with intraduodenal glucose. In the present study, there was little change from baseline in systolic blood pressure or heart rate after oral glucose, whereas systolic blood pressure fell and heart rate rose in response to intraduodenal glucose infusion. The observed cardiovascular response to oral glucose is likely to be due to activation of the gastrointestinal reflex as a result of distension of the stomach. In contrast, diastolic blood pressure fell on both study days and to the same extent; the mechanism responsible for this remains unclear. We found in this study that the magnitude of the observed fall in systolic blood pressure, and increase in heart rate, in response to intraduodenal glucose at $\sim$1.3 kcal/min was predictably less than that observed previously in response to infusion of glucose at a rate of 3 kcal/min (11, 13, 14, 41, 42). By infusing glucose directly into the small intestine at a rate that approximated gastric emptying of the oral glucose load (i.e., mean 1.3 $\pm$ 0.2 kcal/min), the potential “protective” effects of gastric distension were eliminated.

Previous studies have shown that gastric distension influences blood pressure (5, 14, 27, 29, 30, 45, 47, 52). However, a limitation of most of these (8, 27, 45, 47, 52) was that changes in intragastric volumes were not quantified. In our laboratory’s recent study, we demonstrated that as little as $\sim$300 ml of intragastric water markedly attenuates the hypertensive response to intraduodenal glucose at 3 kcal/min, while $\sim$100 ml of intragastric water raises systolic blood pressure 6–8 mmHg above baseline during intraduodenal saline infusion, presumably as a result of gastric distension (14). Our
findings from the present study are consistent with our previous observations that gastric distension resulting from a relatively low volume of intragastric fluid (~300 ml) attenuates the hypotensive response to glucose. Moreover, we found that, 120 min after ingestion of glucose, as little as ~100 ml were effective at maintaining systolic blood pressure at or above baseline levels. We have also evaluated, in healthy older subjects, the effects of water compared with glucose and sucrose drinks (54) and the effects of intragastric water during intraduodenal saline infusion (14) and, in both cases, demonstrated a significant increase in blood pressure, which was evident soon after administration of water. In healthy young adults, in whom ingestion of water does not affect blood pressure, there is evidence of an increase in sympathetic vasoconstrictor activity and cardiac vagal tone, which may relate to its hypoosmotic properties (3). In this group, ingestion of 10% glucose in water has been shown to impair head-up tilt tolerance relative to water ingestion, which is associated with increased heart rate and attenuation of the increase in peripheral vascular resistance (35). The present study and these previous observations (14) dictate that studies to characterize the effects of nonnutrient gastric distension using a barostat device on the responses to enteral glucose in healthy older subjects should be performed, and we have now initiated these (53). It will be important to determine whether the effects of gastric distension are mediated by intragastric volume and/or pressure, the region of the stomach that is distended is important, and the relationship between blood pressure with distension, including the minimum volume/pressure that is effective. Further studies are also indicated to evaluate the effects of “chronic” gastric distension; prolonged distension (i.e., 15 min) using a barostat device, with volumes in the range of 300–600 ml, elevates and then stabilizes blood pressure compared with resting values in healthy young subjects (4).

While there is evidence that gastric distension affects the regulation of splanchnic blood flow, current information is inconsistent and limited to animal studies (33, 40, 50). For example, in the pig, superior mesenteric artery flow has been reported to be decreased (40, 50), increased (50), and unchanged (50) in response to gastric distension, while, in the cat, superior mesenteric artery flow is increased, albeit insignificantly (33). In the present study, a rise in superior mesenteric artery flow was evident from 5 min after oral glucose; however, during intraduodenal glucose, the rise in superior mesenteric artery flow was not statistically significant until 45 min (and much less). Furthermore, we observed that, while systolic blood pressure and heart rate were essentially unchanged after oral glucose, probably as a result of intragastric volume, superior mesenteric artery flow increased substantially and remained elevated above baseline values for the entirety of the study. Van Orshoven et al. (52) reported that proximal gastric balloon stepwise distension using a “barostat” device increased blood pressure and total peripheral arterial resistance in healthy older subjects. Hence, our observations and those of van Orshoven et al. suggest that the sustained increase in superior mesenteric artery flow may be a result of vasoconstriction of the peripheral vasculature by the gastrovascular reflex that is triggered by gastric distension.

Our present study was associated with some limitations. We evaluated only healthy older subjects, none of whom was observed to have postprandial hypotension; hence, the present observations may differ in patients with postprandial hypotension. Our experiment was limited, albeit unavoidable, by its design, such that, to test our hypothesis, subjects ingested an oral glucose load on day 1 and then swallowed a silicone-rubber catheter to receive an intraduodenal glucose infusion on day 2. Hence we were unable to exclude an order effect; this is also despite all of the subjects having previously participated in studies involving intubation. It is surprising that, after the glucose drink, the mean maximum increase in systolic blood pressure, albeit modest, was evident at only ~100 min, suggesting that it was unrelated to either gastric distension or the delivery of glucose into the small intestine and, possibly, reflected nonspecific factors, such as the induction of “stress”. While our laboratory has previously demonstrated that 3D ultrasonography provides a valid measure of gastric emptying of liquid meals (12), it should be noted that some intrindividual variation in gastric emptying of liquids exists. Hence, the technique is associated with some limitations, including those of a more technical nature (2, 7, 16, 19, 20), and represents an estimation of gastric emptying. Furthermore, 3D ultrasonography measures total volume of fluid in the stomach [i.e., drink volume and salivary and gastric secretions (19)]. It is, therefore, possible that progressive dilution of glucose on day 1 resulted in an overestimation of the amount of glucose (kcal) in the stomach over time. It is likely that all of these factors may have contributed to an underestimation of the initial rate of gastric emptying of oral glucose and the subsequent infusion rate of the intraduodenal glucose and hence a potentially reduced blood pressure response to intraduodenal compared with oral glucose. Moreover, the discrepancies in blood glucose concentration between study days support this concept, since variable rates of duodenal glucose delivery have been shown to influence the glycemic response to carbohydrates due to the enhanced stimulation of insulin (6). We also cannot exclude the possibility that differences in glycemia influenced our observations, but this appears unlikely. In particular, intravenous glucose has little, if any, effect on blood pressure (23, 24), and we have reported that there is no relationship between the effects of different carbohydrate drinks on blood pressure and glycemia (55). Animal studies suggest that oral, pharyngeal, and esophageal stimulation have the capacity to modulate blood pressure (17, 34) and may, accordingly, play a role in the postprandial blood pressure response. Nevertheless, the pressor effects of water in older subjects are evident after direct intragastric instillation (14).
Finally, it should be recognized that gastric emptying is predominantly a pulsatile, rather than a continuous, process; most liquefied chyme enters the small intestine as a succession of small gushes (31, 36, 37) that may vary considerably, as forward, interrupted, and reverse flow may all occur (18, 36). Therefore, this may have influenced how accurately individual intraduodenal infusion rates were determined.

**Perspectives and Significance**

Our observations establish that, in healthy older subjects, the fall in systolic blood pressure and rise in heart rate induced by an oral glucose load are less compared with glucose infused intraduodenally at a comparable rate, presumably reflecting the loss of “protective” factors related to gastric distension, a hypothesis that should now be addressed by studies evaluating the effects of nonnutrient gastric distension on the responses to small intestinal glucose. Our observations have clear implications for the management of patients with postprandial hypotension and may also be of relevance in patients who have undergone gastric surgery with a drainage procedure (such as after gastric bypass for morbid obesity) in which the rate of entry of nutrients into the small intestine is accelerated, and for the use of enteral nutrition (intra gastric vs. small intestinal) in the elderly and patients with autonomic dysfunction.

**ACKNOWLEDGMENTS**

Data from this paper have been presented in abstract form at Digestive Diseases Week at the 109th Annual Meeting of the American Gastroenterology Association, San Diego, CA, May 20 2008 (Gentilcore D, Nair NS, Meyer JH, Horowitz M, Jones KL. Gastroenterology 134: A88–A89, 2008).

**GRANTS**

This study was supported by the National Health and Medical Research Council of Australia (NHMRC) of Australia. D. Gentilcore was supported by a Postdoctoral Fellowship (PR 07A 3309) from the National Heart Foundation Council of Australia (NHMRC) of Australia. D. Gentilcore was supported by a Postdoctoral Fellowship (PR 07A 3309) from the National Heart Foundation Council of Australia (NHMRC) of Australia. D. Gentilcore was supported by an Equipment Grant from the NHMRC of Australia and funds from the University of Adelaide and GE Medical Systems Australia.

**REFERENCES**

30. King PM, Adam RD, Pryde A, McDicken WN, Heading RC. Relationships of human antroduodenal motility and transpyloric fluid movement:


