Relation between body weight and the gastric and intestinal handling of an oral caloric load[1]

C. JOHANSSON AND K. EKELUND

From the Department of Medicine, and Laboratory of Gastroenterology, Karolinska Sjukhuset, Stockholm, Sweden

SUMMARY   The gastric and intestinal handling of a standard liquid 300-ml meal (0·89 kcal/ml) was examined in 10 healthy, non-obese subjects by a quantitative multiple-indicator dilution technique. Such a meal contains about one-tenth of the daily energy requirements. The heavier the subject the more energy was transferred from the stomach to the intestine during the first 80 minutes after taking the meal. A high body weight was also associated with a rapid transit through the proximal 70 cm of intestine and the passing of a substantial part of the meal calories to the lower intestine. These circumstances favour a fast incorporation of fed calories. In subjects with lower body weights energy was delivered more slowly from the stomach. They absorbed an equal amount of energy in the proximal intestine as did the heavier subjects, but during longer transit times. The percentage absorption in the investigated segment was therefore higher.

The part played by the human stomach and intestine in regulating the energy influx after feeding, and the influence of various body factors on the gastro-intestinal handling of food are not fully known. We have recently introduced a multiple-indicator dilution technique by which gastric and intestinal function can be measured for several hours after eating. We used it in the present study to investigate the relation between body weight and gastric emptying, intestinal transit, and absorption of energy.

Methods

SUBJECTS

Ten healthy subjects aged 21 to 38 years were studied. None had a history of gastrointestinal symptoms. None was obese (Table 1): only one (subject No. 8) exceeded by 4 kg, the upper limit of normal suggested by the Metropolitan Life Insurance Company.

After an overnight fast the subjects drank 300 ml of a standard liquid meal containing 5 g lactose, 3·6 g protein (skim milk powder), and 5·9 g fat (corn oil) per 100 ml. Polyethyleneglucol (PEG) 3 g/100 ml was added as a marker. The caloric value was 0·89 kcal/ml.

EXPERIMENTAL TECHNIQUE

The multiple-indicator dilution technique has already been described (Johansson *et al.*, 1972b; Lagerlöf *et al.*, 1972). The method of calculation is claimed to be valid because experiments with a simulated stomach and intestine showed only small differences between measured and calculated values for flow volumes and input rates (Johansson *et al.*, 1972a). The reproducibility of the method is high (Johansson, 1974).

The procedure is as follows. The upper gastro-intestinal tract is intubated with three thin tubes the day before an experiment. After swallowing they are allowed to pass by normal peristalsis to their respective correct positions in the gastric antrum, the duodenum descendens, and the jejunum 70 cm from the pyloric sphincter. The test meal containing PEG as a marker is given. Samples from the gastric antrum are thereafter withdrawn at 20-minute intervals (Fig. 1a). From the beginning the duodenal contents are continuously marked by one of the three following indicated substances infused one at a time at a constant rate in the following order, with a change of indicator every 40 minutes: unlabelled vitamin B_{12}, [57]Co-labelled vitamin B_{12}, and [58]Co-labelled vitamin B_{12}. The jejunal contents are siphoned off at intervals of 20 minutes.

The gastric samples are analysed for concentrations of PEG, meal constituents, and hydrochloric acid and the jejunal recoveries for concentrations of duodenal indicator substances, PEG, and meal constituents.

Subject	Body weight (kg)	Body length (cm)	Index*
1	63	181	0·78
2	73	183	0·88
3	58	174	0·78
4	80	180	1·00
5	62	176	0·82
6	73	175	0·97
7	72	186	0·84
8	84	179	1·06
9	85	185	1·00
10	97	196	1·01
Mean	75	182	0·91
± SD	11	6	0·10

Table 1 *Data on subjects investigated*

*Broca's index $\dfrac{\text{body weight}}{\text{body length} - 100}$

Method of calculating jejunal fluid volumes, mean transit times, and gastric emptying

In order to make the concentrations of the different indicators in a jejunal sample comparable all are converted into the same relative unit/ml. The amount of any indicator infused during 40 minutes and the amount of PEG in the meal are therefore given the magnitude 200 units.

c_n = concentration of one indicator in jejunal juice recovered during 20-minute period n (units/ml).

C_n = sum of the concentrations of different indicators in jejunal juice recovered during 20-minute period n (units/ml).

f_n = flow volume at the jejunal sampling site during the 20-minute period n (ml).

$f_n C_n$ = amount of indicator which passed the jejunal sampling site during the 20-minute period n (units).

tm_n = mean transit time (min)—that is, the average time it has taken $f_n C_n$ or the amount of PEG to pass through the proximal 70 cm of the intestine.

$\varDelta tm_n$ = change of transit time during the 20-minute period n (min).

tm_a 0-80 = average transit time of PEG during the first 80 minutes derived as a weighted mean of the transit times of the first four jejunal 20-minute portions of PEG (min).

The jejunal recoveries contain a mixture of the different indicators (Fig. 1b), but the sum of the jejunal concentrations of one indicator multiplied by the jejunal flow volumes in which the indicator is present, $\Sigma f \cdot c$, equals 200 units for every indicator —that is, the amount infused during a 40-minute indicator run. The slope method of Lagerlöf *et al.*,
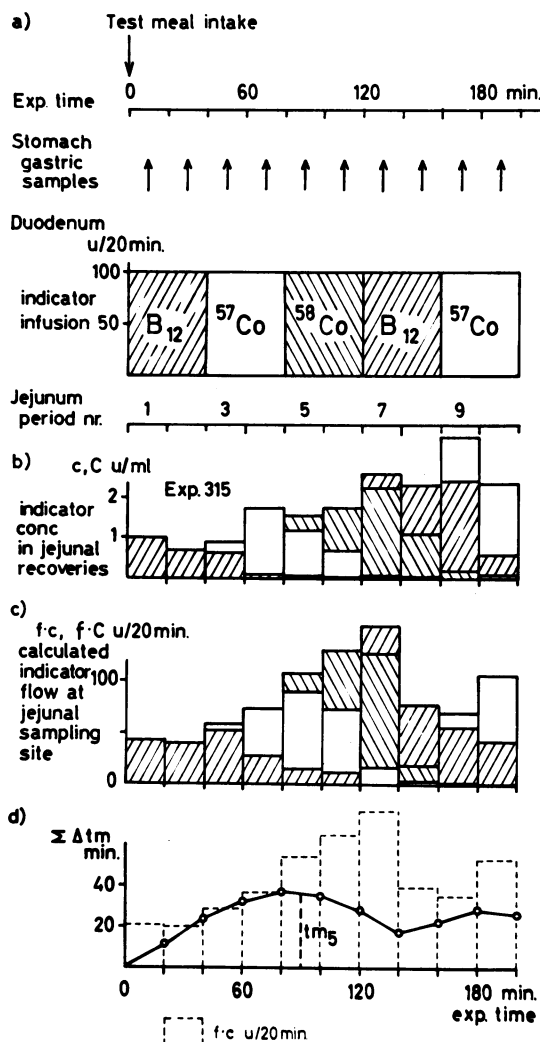

Fig. 1 (a) Schematic representation of experimental procedure. (b) Concentration of different intraduodenally infused indicators in jejunal recoveries (c, units/ml) and the sum of the different concentrations (C, units/ml). (c) Calculated flow of intraduodenally infused indicators at jejunal sampling site (f · C units/20 min). Note that area occupied by each of first three indicators after full transit equals 200 units at jejunal and duodenal level. (d) The mean transit time (tm, min) derived by continuous addition of changes in mean transit time ($\Sigma \varDelta tm$, min).

(1972) provides an approximate value for those indicators that, being infused last, have not completed their transit. Likewise, the sum of the concentrations of PEG in jejunal samples multiplied by the flow volumes amounts to 200 units. From this information and from the jejunal concentrations of the

duodenal indicators and PEG the various flow volumes at the jejunal sampling site (f, ml/20 min) are calculated by computer. From these the amounts of indicator and of test meal marker that pass the jejunal sampling site are determined (Fig. 1c).

The principles of calculating mean transit times in the upper intestine are essentially the same as those devised by Meier and Zierler (1954) for use in systems with constant volume and flow. A constant amount per time (100 units/20 min) of indicator is infused into the duodenum and a variable amount per time (f C units/20 min) passes the jejunal sampling site. There is a simple relationship between the amount of indicator that passes the sampling level during a 20-minute period and the change of mean transit time during the period, which is expressed as

$$\Delta \, tm_n = \frac{20}{100} (100 - f_n \cdot C_n).$$ The addition of consecutive Δ tm:s from the first period onwards, $\Sigma \Delta$ tm min, reflects the mean transit time as a continuous function against the experimental time (Fig. 1d). Representative of an entire 20-minute period is the transit time in the middle of a period

derived from $tm_n = \Delta \, tm_{n-1} + \dfrac{\Delta \, tm_n}{2}$.

From these two equations we get the following time relationship: $f_n C_n$ which passed the jejunal sampling site during the 20-minute period n was infused into the duodenum on average tm_n minutes earlier during 20-Δ tm_n minutes (Fig. 2). By including the concentrations of PEG in the computer flow programme the same time relationships are valid for the jejunal concentrations of PEG and may be used to calculate the gastric emptying of the test-meal marker.

The transfer of PEG to the intestine may be expressed in amounts per minute or per 20-minute periods. Since the concentrations in the gastric antrum are known the emptying rate of the gastric contents, hydrochloric acid, and various meal constituents can be determined. The amount of PEG remaining in the stomach at the end of each 20-minute period may be calculated by subtracting the amount that has emptied. The remaining amounts of PEG and the antral concentrations—the latter corrected for dilution due to duodenal reflux (Lagerlöf et al., 1974)—are used to assess gastric volume and secretion rate.

Calculation of absorption

The absorption from a meal during transit of the proximal intestine (A, mg/70 cm/tm minutes) is obtained from $A_n = L_n - P_n$.

$L_n$mg   is the intestinal load of a nutrient—that is, the amount which should have
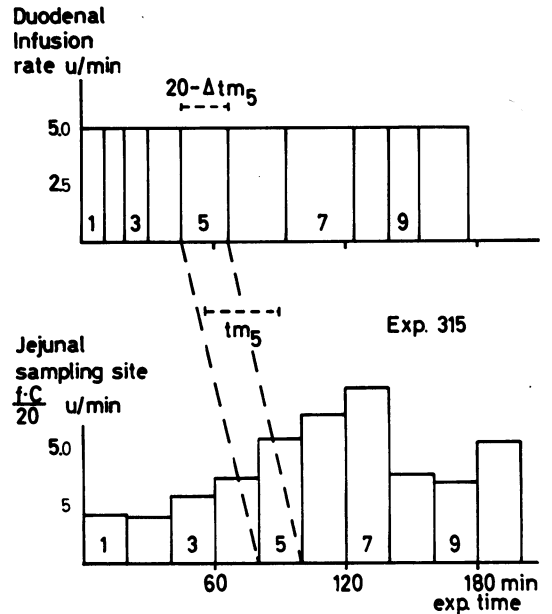

Fig. 2   Time relationships between flow of duodenal indicator at jejunal sampling site $\left(\dfrac{f \cdot C}{20} \, u/min\right)$ and at duodenal infusion site $\left(\dfrac{f \cdot C}{20 - \Delta \, tm} \, u/min\right)$. $f_5 \, C_5$ was infused into the duodenum an average tm_5 min earlier during 20 — $\Delta \, tm_5$ min. In applying this procedure to consecutive jejunal portions the constant infusion rate of the duodenal indicator is re-established.

passed the jejunal sampling site during the 20-minute period n if the absorption had been nil. L_n left the stomach concomitant to the n:th jejunal portion of PEG.

$P_n$mg   is the amount of a nutrient which passed unabsorbed at the jejunal sampling site during the 20-minute period n.

$\dfrac{A_n}{L_n} \cdot 100$ proportion of L_n absorbed during its transit of the proximal 70 cm intestine (%).

$\dfrac{P_n}{L_n} \cdot 100$ unabsorbed proportion of L_n (%).

The amounts of fat, protein, and lactose were translated into their caloric equivalents and added (Rubner, 1885).

Results

Significance was tested with Spearman's non-parametric rank correlation. Linear regressions were

| | Twenty-minute period no. | | | | | | | |
	1	2	3	4	5	6	7	8
Gastric emptying								
Contents (ml)	154 ± 19	122 ± 14	93 ± 13	74 ± 11	67 ± 10	56 ± 11	50 ± 8	50 ± 13
Calories (kcal)	66·7 ± 8·6	41·3 ± 3·5	25·5 ± 3·2	21·5 ± 4·3	23·4 ± 5·3	15·5 ± 2·4	16·7 ± 2·6	
Hydrochloric acid (mEq)	1·7 ± 0·4	3·7 ± 0·9	5·6 ± 1·3	6·1 ± 1·2	4·9 ± 0·9	4·1 ± 0·7	3·9 ± 2·3	
Gastric secretion (ml)	36 ± 9	54 ± 14	56 ± 8	61 ± 8	49 ± 13	38 ± 9	30 ± 80	
Transit times (min)	5·0 ± 0·7	13·2 ± 1·7	16·6 ± 2·1	18·9 ± 3·2	22·0 ± 3·7	24·7 ± 3·9	27·2 ± 3·8	29·6 ± 4·2
Jejunal flow volumes (ml)	135 ± 41	142 ± 17	105 ± 18	71 ± 11	58 ± 10	51 ± 7	50 ± 6	42 ± 5

Table 2 *Gastric emptying and secretion, transit times through the proximal 70 cm intestine, and flow volumes at sampling site in jejunum*
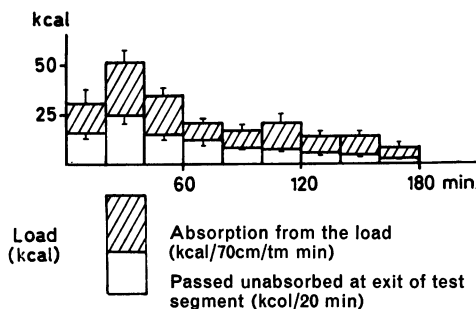
Mean ± SEM per 20 minutes n:10.

Fig. 3 *Absorption of energy from jejunum, 70 cm distal to pylorus. Higher staples represent intestinal loads (kcal) corresponding to each 20-minute period; lower staples represent number of calories which pass jejunal site unabsorbed (kcal/20 min); hatched areas represent absorption from loads during transit of proximal intestine (kcal/70 cm/mean transit time min). Mean ± SEM n:10.*

calculated according to Snedecor. Means are given ± SEM if not otherwise stated.

GENERAL PATTERN OF GASTRIC EMPTYING AND SECRETION AND INTESTINAL ABSORPTION (Table 2, Fig. 3)
After feeding the stomach started to deliver its contents (test meal plus secretion) at a high rate; this gradually declined to remain at a low, fairly stable rate of emptying. Peak emptying rates were reached within 20 minutes in six subjects and within 60 minutes in the remainder. At 80 minutes gastric emptying slowed to an about constant rate in all subjects.

The average delivery rate of calories was maximal soon after ingestion, then decreased, and was constant after the first hour. An average of 53 ± 3% of the calories contained in an average volume of 429 ± 35 ml left the stomach within 80 minutes of taking the meal. Amounts of hydrochloric acid emptied and volumes of gastric juice secreted are shown in Table 2.

Because of individual variations in gastric delivery and intestinal transit times the time of jejunal peak

flow differs from subject to subject. The average jejunal flow rate (7·1 ± 0·9 ml/min) was highest during the second 20-minute period.

The initial test meal transit speed was high. Thereafter it slowed. Transit times and jejunal flow volumes are shown as mean volumes (Table 2), which obscure individual fluctuations. The higher the available load (Fig. 3) the higher was the amount of energy absorbed in the segment. Although the proportion absorbed was fairly constant in relation to the load variations occurred which might have been due to variations in transit times (Johansson 1975). Soon after the meal, when transit through the proximal intestine was rapid, the percentage energy absorption was lower and a considerable amount was unabsorbed.

RELATION BETWEEN BODY WEIGHT AND GASTRIC AND INTESTINAL HANDLING OF AN ORAL LOAD (Table 3)
The gastric delivery rate of energy to the intestine was higher the heavier the subject. The correlation between the body weight and the number of calories emptied during the first 80 minutes after the meal was highly significant ($p < 0.001$) (Fig. 4). The linear relationship became increasingly convincing with the lapse of time from ingestion; tests for
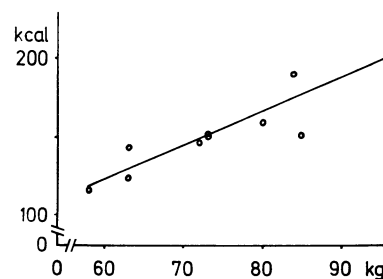

Fig. 4 *Relation between body weight (kg) and emptied energy during 80 minutes after meal intake (kcal). Emptied kcal = 2·13 body w − 4·45 (r + 0·91; n:10; SE (b) 0·35).*

Subject no.	Body weight (kg)	Gastric emptying			Gastric secretion (ml)	tm_a 0-80 (min)	Jejunal flow volume (ml)	Absorption		
		Volume (ml)	Energy (kcal)	Hydrochloric acid (mEq)				L (kcal)	P (kcal)	A (kcal)
1	63	368	124·3	10·5	115	13·7	320	112·4	45·2	67·7
2	73	343	157·6	20·7	198	10·1	387	138·8	57·5	81·3
3	58	416	117·5	11·6	98	25·8	222	90·1	28·3	61·8
4	80	358	159·7	12·0	143	15·9	257	139·7	53·2	86·6
5	62	393	144·8	13·0	181	17·6	288	128·6	43·3	85·3
6	73	276	151·1	2·3	15	6·9	382	147·2	112·0	35·1
7	72	514	146·0	21·9	288	11·7	460	140·5	86·7	53·8
8	84	536	190·5	16·3	279	10·5	632	120·3	67·0	53·3
9	85	439	152·9	22·0	344	8·3	815	127·0	71·0	56·1
10	97	655	212·2	40·3	345	9·8	747	203·7	130·9	73·0

Table 3 *Gastric and intestinal variables during the first 80 minutes after meal*

calories emptied 40 and 60 minutes after ingestion gave correlation coefficients of + 51 and + 75 respectively.

Whereas there was no significant correlation between the body weight and the emptied hydrochloric acid or the emptied volume, the volume of gastric secretion during the first 80 minutes after the meal was larger the heavier the subject ($p < 0.05$).

The passage through the proximal 70 cm intestine was more rapid in heavy subjects ($p < 0.05$). The average transit time during the first 80 minutes was inversely proportional to the body weight (Fig. 5).
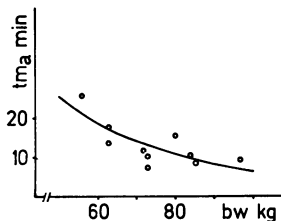

Fig. 5 *Relation between body weight (kg) and average transit time during 80 minutes (tm_a, min) after ingestion of meal. Curve was drawn according to:*

$$tm_a\ 0\text{-}80 = \frac{1890}{body\ w} - 12.7\ (r\ 0.73;\ n{:}10;\ SE\ (b)\ 633).$$

The absorption of energy (65.4 ± 5.2 kcal) from the first 80-minute load (134.8 ± 9.3 kcal) during its transit of the proximal 70 cm of the intestine was independent of the body weight. The heavier the subject the more calories ($p < 0.05$) left the test segment unabsorbed and the higher were the fluid volumes ($p < 0.02$) which left the test segment.

Discussion

Hunt and Stubbs (1975) found that the rate of emptying of the stomach slowed as the caloric density of a meal increased. This was shown with test meals of different compositions and volumes. Thus

calories per time is an adequate way of expressing the inhibitory effect on gastric emptying of any composite meal. The hyperbolic shape of the curve suggests that the protective mechanism against overloading of the intestine is effective at caloric densities below 1 kcal/ml, whereas any further increase in the density is likely to result in the delivery of more calories to the intestine per time unit. Since the gastric emptying rate should influence the rate of incorporation of fed calories. Hunt and Stubbs (1975) examined the dietary records of subjects of various weights and found that meals consumed by heavy people were of a higher caloric density.

Another aspect of the relation between body weight and gastric emptying is shown in the present paper. After subjects of varying weights had been fed with a composite meal of a caloric density of 0·89 kcal/ml the caloric transfer rate to the intestine was higher the heavier the subject. The relationship between the body weight and emptied calories became increasingly direct with the time that had elapsed since eating and was highly significant for the amount of energy transferred during the initial period of 80 minutes.

After a meal the stomach starts to empty its contents at a high rate. The presence of digested food in the duodenum (Hunt and Knox, 1968; Knox and Mallinson, 1971) triggers mechanisms by which the gastric propulsion is inhibited and the emptying of the gastric contents (test meal plus secretion) is slowed. Although we have not yet identified the mechanisms of this feed-back system, some of the ways in which they operate are evident.

As previously shown (Johansson, 1974), the interval between a meal and any sign of inhibition of gastric propulsion is influenced by the composition of the meal. Analysis of individual emptying patterns in the present series further shows that the promptness with which inhibition is initiated is related to the time taken to establish full inhibition—that is, the time that elapses before a constant, slow rate of emptying is established. The emptying patterns in
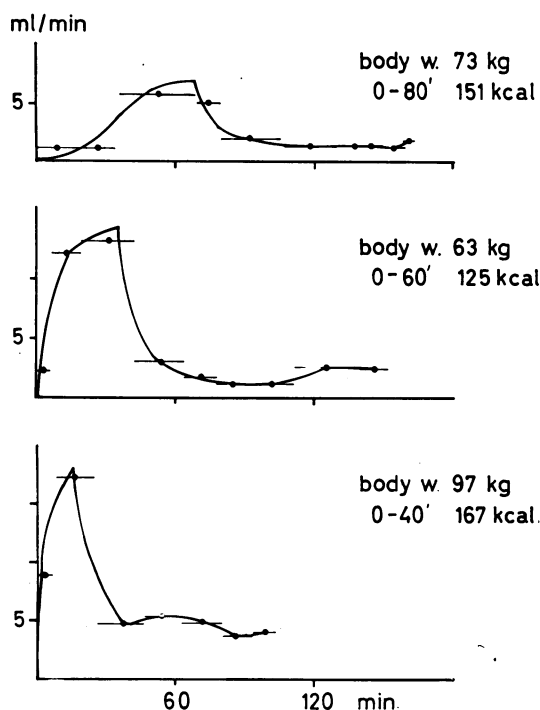
ml/min

body w. 73 kg
0-80' 151 kcal

body w. 63 kg
0-60' 125 kcal

body w. 97 kg
0-40' 167 kcal

Fig. 6 *Speed of emptying of gastric contents (ml/min) in three experiments.*

three experiments (Fig. 6) illustrate this. A slow initial emptying rate (Fig. 6 top), which is equivalent to prompt inhibition, is followed by a comparatively quick emptying rate and a late change to a constant emptying rate. The opposite situation prevails in the lower experiment (Fig. 6 bottom), in which slow initiation of inhibition is followed by a steady transfer rate 40 minutes after ingestion of the meal. If we accept that the gastric inhibition is triggered by digested food in the duodenum the logic of these examples is evident. The immediate delivery of a larger caloric load to the intestine should elicit a larger inhibitory response and consequently earlier full inhibition.

In the present series the initial gastric emptying rate was not weight dependent nor was the interval from feeding until a constant emptying rate was established. A positive correlation ($p < 0.001$), however, existed between the body weight and the total number of calories emptied before a steady transfer rate was reached. This seems to indicate that the heavier the subject the more emptied energy is needed to establish full gastric inhibition. The existence of these initial and adaptive phases of the gastric emptying pattern after feeding explains why the correlation between body weight and emptied energy increases with time from food intake. After

80 minutes these phases were completed in all cases and the gastric contents then began to empty at slow constant rates.

The faster gastric secretion rates seen in the heavy subjects were not paralleled by a larger total secretory response. The volume of secretion from meal intake until 97.5% of the test-meal marker had left the stomach amounted to an average of 270 ± 35 ml and was unrelated to body weight.

Hydrochloric acid infused into the stomachs of fasting human subjects delays gastric emptying in proportion to the concentration of acid in the infusate (Hunt and Knox, 1965). It was uncertain whether hydrochloric acid, secreted and emptied in response to an ingested meal, had an inhibitory effect on gastric emptying. Our findings showed that the higher the gastric secretion rate the more rapidly were the gastric contents transferred to the intestine ($p < 0.02$). This agrees with previously reported results (Johansson *et al.*, 1976) and points to a positive correlation between the gastric secretion rate and the gastric propulsive motility after physiological stimulation.

Another reflection of the adjustment to body weight were the higher average transit times through the proximal intestine in the heavy subjects. It might be argued that rapid transit was a consequence of the higher energy transfer rate from the stomach,
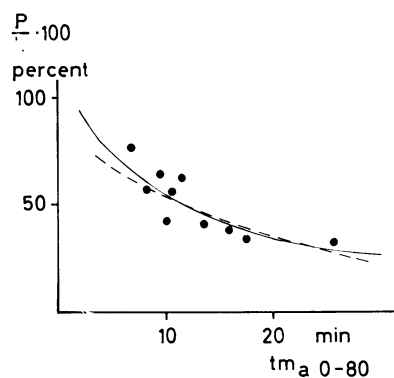
$\frac{P}{L} \cdot 100$

percent

^{tm}a 0-80

Fig. 7 *Relation between percentage absorption (area above curves) and transit time. $\frac{P}{L} \cdot 100$ is percentage of first 80-minute load which passes unabsorbed at exit of test segment. $tm_{a\ 0-80}$ is average transit time for the first four jejunal 20-minute portions of PEG. Unbroken curve was drawn according to: $\frac{P}{L} \cdot 100 = \frac{1005}{tm_{a\ 0-80}} + 11.48$ (r 0.87; n:10; SE (b) 200). Hatched curve was drawn according to: $\ln \frac{P}{L} \cdot 100 = 4.452 - 0.0448\ tm_{a\ 0-80}$ (r 0.83; n:10; SE (b) 0.0106).*

but no simple relationship existed between the gastric delivery rate of calories or contents and the time taken to traverse the upper intestine.

It has previously been shown (Johansson, 1975) that absorption in a segment depends on the size of the load and on the duration of its contact with the intestinal mucosa—that is, the time taken to traverse the segment. Data from the present series support the earlier findings in that the amount absorbed from the first 80-minute load was higher when the average transit time was longer ($p < 0.02$).

Figure 7 shows how a rapid transit greatly limits the percentage absorption (area above curves) in a segment, and consequently is associated with the propagation of a larger proportion of the first 80-minute load of energy to lower parts of the intestine. Hence the more rapid transit in the heavier subjects limited absorption from their early high loads and more calories left the proximal intestine unabsorbed and were exposed to a larger mucosal area. These circumstances should result in a faster incorporation of fed calories in heavy than in light subjects.

References

Backman, L., and Hallberg, D. (1974). Small-intestinal length. An intraoperative study in obesity. *Acta Chirurgica Scandinavica*, **140**, 57-63.

Hunt, J. N. (1974). *The Bengt Ihre Lecture*. Stockholm, Sweden.

Hunt, J. N., and Knox, M. T. (1965). The effects of acids on gastric emptying. *Journal of Physiology*, **181**, 63 p.

Hunt, J. N., and Knox, M. T. (1968). Regulation of gastric emptying. In *American Physiological Society Handbook*, Section 6, 1917-1935. American Physiological Society: Washington.

Hunt, J. N., and Stubbs, D. F. (1975). The volume and energy content of meals as determinants of gastric emptying. *Journal of Physiology*, **245**, 209-225.

Johansson, C. (1974). Studies of gastrointestinal interactions. *Scandinavian Journal of Gastroenterology*, **9**, suppl. 28.

Johansson, C. (1975). Studies of gastrointestinal interactions. 7. Characteristics in the absorption pattern of sugar, fat and protein from composite meals in man. A quantitative study. *Scandinavian Journal of Gastroenterology*, **10**, 33-42.

Johansson, C., Ekelund, K., Kulsdom, N., Larsson, I., and Lagerlöf, H. (1972). Studies of gastrointestinal interactions. 2. Calculation of gastric evacuation in an *in vitro* model. *Scandinavian Journal of Gastroenterology*, **7**, 391-393.

Johansson, C., Lagerlöf, H., and Ekelund, K. (1976). Quantitative and qualitative aspects of the gastric secretory response after meals of different compositions. *Mount Sinai Journal of Medicine* (In press).

Johansson, C., Lagerlöf, H., Ekelund, K., Kulsdom, N., Larsson, I., and Nylind, B. (1972). Studies of gastrointestinal interactions. 3. Determination of gastric secretion and evacuation, biliary and pancreatic secretion, intestinal absorption, intestinal transit time and flow of water in man. *Scandinavian Journal of Gastroenterology*, **7**. 489-499.

Knox, M. T., and Mallinson, C. N. (1971). Gastric emptying of fat in patients with pancreatitis. *Rendiconti*, **3**, 115.

Lagerlöf, H., Ekelund, K., and Johansson, C. (1972). Studies of gastrointestinal interactions. A mathematical analysis of jejunal indicator concentrations used to calculate jejunal flow and mean transit time. *Scandinavian Journal of Gastroenterology*, **7**, 379-389.

Meier, P., and Zierler, K. L. (1954). On the theory of the indicator-dilution method for measurement of blood flow and volume. *Journal of Applied Physiology*, **6**, 731-744.

Rubner, H. (1885). Calorometrischen Untersuchungen. *Zeitschrift für Biologie*, **21**, 337-411.