Transmucosal triglyceride transport rates in proximal and distal rat intestine in vivo

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Abstract Transmucosal transport rates for triolein in proximal and distal intestine were compared in unanesthetized rats. Emulsified [1-^{14}C]triolein together with bile and pancreatic juice from donor rats was infused for 6 hr into either the duodenum or the midpoint of the small intestine at such a rate that absorption was essentially complete in both regions of the intestine. Lymph was collected from the thoracic duct during triolein infusion and for an additional 6-hr period. The decrease in the rate of lymphatic output of labeled fat was found to follow a simple exponential function in all animals. This rate of decrease (decay rate) was used to calculate the half-times of lipid turnover through the intestinal wall and the fractional output rates. Distal intestine transported lipid 40% more slowly than proximal intestine, and the difference was associated with a greater accumulation of triglyceride in the distal intestinal wall. Chylomicron synthesis and/or release is the rate-limiting step for distal lymphatic fat transport in vivo, whereas fat uptake from the lumen is rate limiting for proximal intestine.

Supplementary key words lipid transport · intestinal transport

In a recent study, Clark, Lawergren, and Martin (3) demonstrated that distal rat intestine accumulated more fat than proximal intestine during maximal triolein absorption in vivo. The regional tissue lipid concentrations best fitted a mathematical model that suggested that maximal lipid uptake rates from the lumen were equal in most regions of intestine but that distal intestine was relatively deficient in triglyceride output on the serosal side. The present study was designed to test this model by direct measurement of fractional triglyceride output rates in proximal and distal intestine using direct regional perfusion under conditions where uptake from the lumen was complete.

HYPOTHESIS

In general, during absorption of a ^{14}C-labeled lipid the tissue lipid concentration, y, at any given time will be determined by both input and output rates such that

$$dy/dt = aA - by \qquad \text{Eq. 1}$$

where y is the amount of lipid ^{14}C in the tissue at any given time, b is the fraction of the tissue lipid ^{14}C content leaving the tissue in unit time, A is the amount of lipid ^{14}C in the lumen at any given time, and a is the fraction of this luminal lipid ^{14}C entering the tissue in unit time.

If uptake is complete at the time that luminal administration is stopped, thereafter $aA = 0$, and Eq. 1 reduces to

$$dy/dt = -by \qquad \text{Eq. 2}$$

i.e., the tissue lipid ^{14}C concentration is then determined by the output rate only.

If b is independent of y, as suggested by the mathematical model (3), the differential Eq. 2 can be solved thus:

$$\ln\ y/y_0 = -bt \qquad \text{Eq. 3}$$

where y_0 is the amount of lipid ^{14}C in the tissue at the time the meal infusion is stopped, and y is the amount of lipid ^{14}C in the tissue at any time after uptake has ceased and while the tissue lipid ^{14}C concentration is decreasing (decay period).

When $y = 0.5\ y_0$, then

$$\begin{aligned} t &= t_{1/2} \\ -\ln\ 2 &= -bt_{1/2} \\ 2.303\ \log\ 2 &= bt_{1/2} \\ t &= 0.693/b \end{aligned} \qquad \text{Eq. 4}$$

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Abbreviations: BP, bile and pancreatic juice.

or the fractional output rate, $b = 0.693/t_{1/2}$ Eq. 5

In the case of long-chain triglyceride, substantially all the tissue lipid is removed via the lymphatic system under normal conditions, and $t_{1/2}$ may be measured by following the decrease (decay) of the lipid output in thoracic duct lymph after lipid infusion is stopped, under conditions where luminal uptake approaches 100%. The fractional output rate determined from the decay in lymphatic output (b') may then be calculated according to Eq. 5.

If the decay in lipid output rate follows first-order kinetics, then the determination of b' does not require the achievement of a steady output before beginning the decay measurements. In the present studies, however, lipid infusions were continued until a steady output was reached in each animal in order to determine in addition, if possible, the maximum capacities for lipid transport by proximal and distal small intestine.

METHODS

Surgery and postoperative care of animals

Male rats of the Wistar strain, 280–320 g, were used. The animals were maintained from weaning on an ad lib. diet containing 6.0% fat (Purina laboratory chow 5010, Ralston Purina Co., St. Louis, Mo.) and tap water. Each animal was prepared with four cannulas: (*1*) abdominal thoracic duct for lymph collection, (*2*) bile plus pancreatic juice diversion, and (*3*) and (*4*) two intraintestinal infusion cannulas inserted into either the duodenum (proximal) or the intestinal midpoint (distal). Under ether anesthesia, a right subcostal incision was made and the thoracic duct was intubated just above the cisterna chyli, using heparinized vinyl tubing (0.5 mm ID). The common duct was then cannulated at its entry into the duodenum with flanged polyethylene tubing (PE 10; 0.1 mm ID). Flanged vinyl or polyethylene tubing (PE 50; 0.5 mm ID) was used for the two intestinal infusion cannulas, which were inserted about 0.5–1 cm apart through small incisions in the intestinal wall directly into the intestinal lumen and secured by firmly drawn purse-string sutures using 5-0 silk. The free ends of the four cannulas were exteriorized through a stab wound in the midline of the abdomen. The animals were placed into restraint cages for 40–46 hr to recover from the surgical stress (4). Infusion of ice-cooled bile and pancreatic juice (BP) collected from donor rats was begun immediately after surgery (0.75 ml/hr) and continued without interruption for the duration of the experiment. Animals from both groups were paired to minimize possible variation due to slight differences in the infused BP composition. However, subsequent statistical evaluation revealed that BP composition was not a significant variable under the present experimental conditions. A continuous infusion of glucose–KCl–NaCl (1.0%–0.03%–0.85% w/v) was also administered through the other infusion cannula for maintenance of fluid, electrolytes, and some calories at 2.293 ml/hr for the first 24 hr and thereafter at 1.146 ml/hr, except during lipid infusion. Lymph flow was usually stable after 24 hr, when it approximately equaled the saline infusion rate (1.1 ml/hr). Lipid infusions were administered on the second and third postoperative days (48 hr and 72 hr after surgery) at 1.146 ml/hr using a constant infusion pump (Harvard Apparatus Co., Inc., Millis, Mass.).

Triolein emulsion

Glyceryl,tri[1-^{14}C]oleate (Amersham/Searle Corp., Arlington Heights, Ill; stated purity >99%, checked by thin-layer chromatography) was added to carrier triolein (Sigma Chemical Co., St. Louis, Mo; purity >95% as stated by the supplier). The mixture was stirred vigorously at room temperature for 1–2 hr. When isotopically homogeneous (6 μCi/g of triolein), triplicate 10-μl aliquots from different levels of the container were weighed, the radioactivity was determined by liquid scintillation counting in Bray's solution (5), and the specific activity of the oil was calculated (approximately 4000 dpm/μeq of fatty acid). A solution containing dextrose (4.15%), Pluronic F-68 (0.3%), and vegetable lecithin (1.2%) in water was prepared by sonication at 45°C for 1–2 min. To 485 ml of this solution, 15 ml of ^{14}C-labeled triolein oil was added, and the mixture was resonicated several times at 40–45°C until the resulting emulsion was isotopically homogeneous. The [^{14}C]triolein emulsion, which contained approximately 110 μeq of fatty acid/ml, was then refrigerated for 3–4 days and sonicated briefly several times to ensure continued homogeneity. The final emulsion was stored in 80-ml batches at −20°C. Only minimum resonication was required on thawing even after 1 yr of storage.

Experimental procedures

Early on the second postoperative day (first experimental day), the glucose–KCl–NaCl infusion was replaced by [^{14}C]triolein emulsion (approximately 130 μeq of fatty acid/hr) for 6 hr. Thereafter, the saline infusion was again administered. On the following morning, the lipid infusion was repeated as on the previous day but the animals were killed at the end of the 6-hr infusion period.

Aliquots of lymph were collected at 30-min intervals at room temperature into graduated centrifuge tubes containing sufficient EDTA to reach a final concentration of 0.1% before the lipid infusion (basal), during the 6 hr of test meal infusion, and, on the first experimental day, for a further 6 hr after return to the saline infusion. The overnight output between the two experimental days was collected in one batch. Aliquots of lymph (100 μl from each collection

period) were counted in Bray's solution. In some animals, chylomicrons were prepared by centrifugation and their size distribution and composition were determined. Data from these experiments will be described in detail elsewhere.

On the second experimental day, immediately after the infusion period, the animals were quickly removed from their cages and killed by cervical dislocation. The small intestine was washed once in situ, from duodenum to ileum as a whole for the proximally infused group and in two parts for the distally infused group, with 30 ml of ice-cooled sodium taurocholate (2 mM) in 0.15 M NaCl, pH 6.3, and with a further 30 ml immediately after removal from the animal. The intestine was stripped by finger pressure after each wash. Intestinal washes were collected into a chilled graduated cylinder and kept at 4°C while the intestine was sectioned on an ice-cooled glass plate (about 10 min). The whole intestine was divided into 10 approximately equal weight segments, of which the first 6 (proximal) or the last 7 (distal) were transferred immediately to preweighed, capped, homogenizing tubes containing 2 ml of acidified (pH < 1) 0.15 M NaCl as described previously (3). The tissues were weighed, homogenized, and extracted once with 6 ml of toluene–ethanol 2:1 (v:v) and once with 1 ml of toluene (6). Aliquots (1 ml) of the combined toluene extracts were removed for determination of total radioactive lipid by liquid scintillation counting, and other aliquots were separated into lipid classes by thin-layer chromatography. The volumes of the intestinal washes were recorded and the washes were mixed thoroughly. Duplicate 2-ml aliquots were acidified with HCl to pH < 1 and were immediately transferred to graduated centrifuge tubes containing 6 ml of toluene–ethanol 2:1 for extraction of lipid. Gastric (proximal group) or cecal (distal group) contents were separately washed with 0.15 M NaCl; the volumes were recorded and the washings were mixed thoroughly. The radioactivity in duplicate 0.5-ml aliquots of all washes was estimated by liquid scintillation counting, and the total luminal recoveries of unabsorbed radioactivity and the lipid absorption rates were calculated.

Bile and pancreatic juice infusion

BP was collected in a single pool that was used for all the animals. The pool was frozen in batches sufficient for a single day. A fresh batch was thawed each morning and was kept at 4°C during infusion at 0.75 ml/hr per rat, using a cassette pump (Manostat Corp., New York). Initially, the lipolytic activity of the BP pool was measured at the end of each experimental day as follows.

Bile and pancreatic juice, 1.5 ml, taken from the returning pool was added to 2.5 ml of the test meal (a ratio approximately equal to that of the luminal infusions) in a 25-ml Erlenmeyer flask. The mixtures were incubated at 37°C in a Dubnoff metabolic shaking incubator for 1 hr. Duplicate 0.5-ml aliquots of the mixtures were then transferred to graduated centrifuge tubes containing 1.5 ml of acidified 0.15 M NaCl (pH < 1) and extracted with 6 ml of toluene–ethanol 2:1. Aliquots of the toluene phase were removed for the determination of total radioactivity by liquid scintillation counting, and other aliquots were separated into lipid classes by thin-layer chromatography. In several samples analyzed, only about 20% of the ^{14}C-labeled lipid was found in triglyceride after 1 hr. In later experiments, when it became apparent that uptake from the lumen was virtually complete in all animals irrespective of BP composition, no analyses were performed.

Thin-layer chromatography

Lipids extracted into toluene were separated on silica gel G plates (Analtech, Inc., Newark, Del.) using the two-stage, one-dimensional separation system previously described (6). The chromatographic fractions (phospholipid, monoglyceride, free fatty acid, 1,2-diglyceride, 1,3-diglyceride, triglyceride) were then counted in Bray's solution without further extraction of labeled lipid from the silica gel.

Liquid scintillation counting

All samples (lymph, 100 μl; intestinal, gastric, and cecal washes, 0.5 ml in duplicate; triolein emulsions, 50 μl in triplicate; toluene extracts of lipid from intestinal tissue, 1 ml; silica gel fractions from thin-layer chromatograms) were counted in Bray's solution in a Beckman three-channel liquid scintillation system, LS-250. Count rates obtained were corrected to disintegration rates (dpm) using the external standard ratio method, according to standard quench curves prepared with 0.15 M NaCl as the quenching agent.

Evaluation of data

For each animal, a least squares regression line relating the logarithm of the lymphatic ^{14}C-labeled lipid output rate to the elapsed time after lipid infusion stopped was determined using linear regression analysis, and the half-time of the decay in lipid output rate ($t_{1/2}$) was calculated from the slope of the line. The mean correlation coefficients for the proximally and distally infused groups were 0.991 and 0.989, respectively.

RESULTS

Proximal vs. distal intestinal triolein transport

Table 1 shows the total ^{14}C-labeled lipid recoveries on the first and second experimental days in proximal and distal intestine. Because the total recovery (lymph plus intesti-

TABLE 1. Kinetics of triolein transport through proximal and distal small intestine

	Proximal	Distal	P
Lymphatic output at 6 hr[a]			
Day 1	72.9 (2.8)[b,c]	59.9 (2.3)[c]	<0.005
Day 2	77.1 (2.6)[c]	65.2 (2.3)[c]	<0.02
Absorption rate (μeq fatty acid/hr)	129.8 (1.6)	126.4 (1.5)	NS
Infusion rate (μeq fatty acid/hr)	131.5 (1.3)	132.3 (1.2)	NS
$t_{1/2}$ of decay (hr)	0.847 (0.032)	1.151 (0.062)	<0.01
Fractional output rate b' (per hr)	0.824 (0.032)	0.614 (0.035)	<0.005
Tissue lipid at 6 hr[a]	13.9 (1.4)	22.3 (2.7)	<0.05
Total recovery[a]			
Day 1	94.9 (2.7)[c]	92.3 (1.4)[c]	NS
Day 2	93.0 (1.4)[c]	92.8 (1.5)[c]	NS
n	5	7	

[a] % of total ^{14}C-labeled lipid infused.
[b] Means (SE).
[c] First and second experimental days not significantly different.

nal wall plus lumen, as appropriate) in both groups was more than 90% on both days and did not differ significantly between day 1 and day 2 within groups, transmucosal transport of [^{14}C]triolein was effectively measured in this experimental system.

The tissue ^{14}C-labeled lipid concentrations (**Table 2**) show that no more than half of the intestine contained ^{14}C-labeled lipid. Moreover, by inspection at laparotomy, the mesenteric lymphatics were white only in the test regions and, in particular, no lipid appeared to be absorbed proximally to the infusion site in distally infused animals.

Fig. 1 shows the pattern of lymphatic ^{14}C-labeled lipid output from proximal and distal intestine. During the infusion period, the proximal output rate reached a steady state as early as 3 hr after the infusion began and plateaued at 98% of the infusion rate. Output from the distal intestinal wall was much slower initially and leveled off at 85% of the infusion rate only after 5 hr of infusion. After lipid infusion was stopped, the decay in ^{14}C-labeled lipid output in both groups of animals followed simple first-order kinetics with significantly different half-times (Fig. 1 and Table 1). Because the lymphatic output during the 6-hr infusion period did not differ between the first and second experimental days for both groups (**Fig. 2** and Table 1), the uptake rate from the lumen measured after 6 hr on the second day indeed reflected the conditions present at the same time on the first day.

Absorption from the lumen approached 100% in both proximal and distal intestine when measured at 6 hr (Table 1) and also after 3 hr in a single pair of animals

TABLE 2. ^{14}C-labeled lipid content in regions of gastrointestinal tract

	Proximal Group (4)[a]							
	Stomach Lumen *	Intestinal Segments 1	2	3	4	5	6	Total in Intestinal Wall
Mean	7.8	12.9[b]	19.2	30.6	31.8	13.7	0.9	110.5
SE	1.2	3.3	3.4	8.3	3.8	2.3	0.1	10.3

	Distal Group (5)[a]								
	Intestinal Segments 4	5[c] *	6	7	8	9	10	Total in Intestinal Wall	Cecal Lumen
Mean	0.3	28.2	100.9	43.3	3.6	0.5	0.3	176.7	1.3
SE	0.1	4.3	15.8	5.0	1.4	0.05	0.05	20.5	0.8

Asterisk indicates location of infusion cannula.
[a] Number of animals in parentheses.
[b] μeq of fatty acid/segment.
[c] Some cannulas were inserted 1-2 cm proximal to the intestinal midpoint so that segment 5 contained some radioactivity.

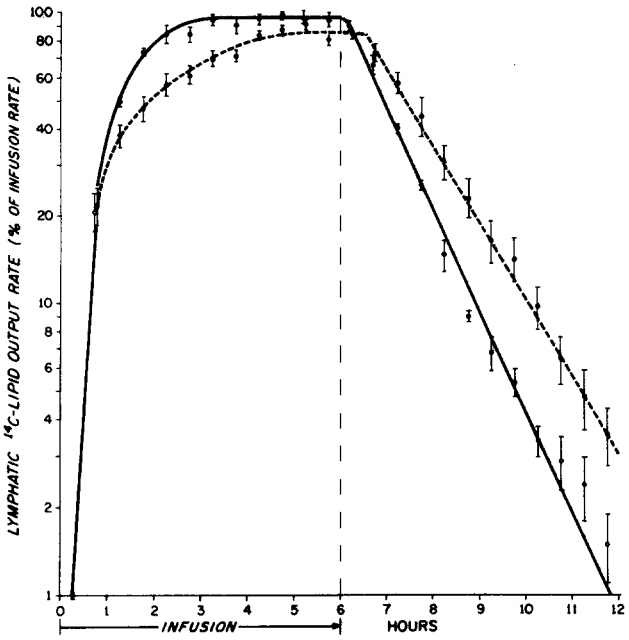

Fig. 1. Lymphatic ^{14}C-labeled lipid output rates in proximally and distally infused rats. Emulsified [^{14}C]triolein infused at 130 μeq of fatty acid/hr for 6 hr. Mean and SE; O, proximal (5); ●, distal (7).

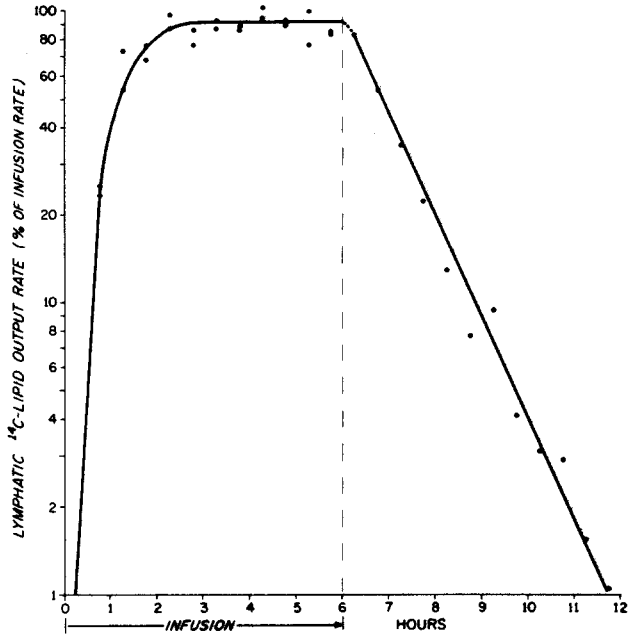

Fig. 2. Lymphatic ^{14}C-labeled lipid output rates on day 1 and day 2. Emulsified [^{14}C]triolein infused at 130 μeq fatty acid/hr for 6 hr. Single representative animal from proximal group; ●, first experimental day; O, second experimental day.

(data not shown). Thus, in both groups, the lymphatic ^{14}C-labeled lipid output measured after the infusion stopped was determined solely by the rate of release of lipid that was already present in the intestinal tissues.

The mean $t_{1/2}$ for the distal intestine derived from individual decay curves was about 35% greater than that for the proximal intestine (Table 1), and the corresponding fractional outputs, b', also differed significantly. The total ^{14}C-labeled lipid found to have accumulated in the intestinal wall at the end of the 6-hr infusion period was greater in distally infused animals (22.3% of the total infused lipid in distal intestine compared with 13.9% in proximal intestine). Thin-layer chromatographic analysis of the tissue ^{14}C-labeled lipid showed that more than 90% of the label was in triglyceride in both proximal and distal intestine.

DISCUSSION

The results demonstrated that the fractional turnover rate of [^{14}C]triolein through the intestinal wall in vivo was about 40% slower in distal compared with proximal halves of rat intestine, under experimental conditions in which the luminal uptake rates were complete in the two regions. The hypothesis suggested by Clark et al. (3), that slower distal transmucosal lipid transport was responsible for the higher tissue lipid accumulation in distal compared with proximal intestine when uptake rates were maximal, is thus supported by the present experiments. As in the previous study, substantially all the ^{14}C-labeled lipid recovered from the tissue was triglyceride; the slower distal transport was therefore attributable to a relative deficiency in chylomicron synthesis or release in this half of the small intestine.

Clark et al. (3) also showed that tissue lipid concentrations in most regions of intestine reached a steady state after 4–6 hr of maximal steady absorption by the whole intestine. In that study, the fractional output rate for triolein in distal segments 6–8 (b) was similar to b' determined from the decay in lipid output in the present study (0.58/hr and 0.61/hr) despite a 50% increase in distal mucosal lipid pool size under the maximal infusion conditions. In proximal intestine, however, the triglyceride pool size was not greater during maximal-rate compared with low-rate infusion, yet the fractional output rate increased markedly (compare $b' = 0.82$/hr with $b = 2.6$/hr averaged over segments 1–5). Thus, in proximal intestine, a higher efficiency was achieved under maximal absorption conditions compared with the low infusion rate of the present study. Because a true steady state was achieved here during both high and low infusions, it is clear that proximal intestine has the capacity to increase the efficiency of chylomicron output as the uptake rate from the lumen increases.

The kinetics of triglyceride transport by proximal intestine may be described as follows. Because the tissue ^{14}C-

labeled lipid was always predominantly triglyceride even during maximal transport, the time required to reesterify the absorbed fatty acid into triglyceride in the mucosal cell must have been negligible under all infusion conditions examined. If synthesis and release of chylomicrons is considered as one compartment and the bulk mucosal triglyceride as a separate compartment, the total time required for the transport of absorbed lipid into the lymphatics will approximate the time required for chylomicron formation and release from the triglyceride pool. Suppose the mucosal cell has an unlimited capacity for chylomicron synthesis. Then, once a steady state is achieved, the tissue ^{14}C-labeled lipid content is determined only by the time required for the sequence of intracellular reactions to be completed, and a constant fraction of the total tissue lipid will be present in prechylomicrons awaiting release from the tissue irrespective of the total amount of triglyceride present. Under such a system, when the lipid absorption rate is increased a higher efficiency of chylomicron formation will result, and both the lipid output rate and the fractional output rate will increase. The combined data from both low and maximal infusion studies suggest that these conditions were met in proximal rat intestine.

On the other hand, if the chylomicron synthesis rate were relatively limited, while the triglyceride pool was expandable, then a steady output rate could be obtained in the face of an increasing tissue lipid concentration as lipid infusion continued. This occurred in distal rat intestine after the fifth hour of low-rate infusion. In the maximal absorption study by Clark et al. (3), a steady state for total tissue lipid concentration was ultimately achieved in the distal intestine by 6 hr, in contrast to proximal intestine, which stabilized very rapidly. However, under low infusion conditions the lymphatic output from the distal small intestine became constant at 85% of the infusion rate after 5 hr of infusion, suggesting that a limit to the capacity of distal intestine for chylomicron synthesis and release had been reached after 5 hr, although the triglyceride pool was not yet fully saturated. Careful examination of the lymphatic ^{14}C-labeled lipid output rates in the early stages after infusion was stopped also suggests saturation of the prechylomicron pool. In the general case, if input to a system is interrupted or reduced after a pool is saturated, the subsequent decay in output rate should initially follow zero-order or mixed zero- and first-order kinetics. In the present study, the lymphatic ^{14}C-labeled lipid output rate during the first collection period after the infusion was stopped was higher than that expected for the first-order decay process that appeared thereafter (see Fig. 1), implying that saturation somewhere in the system probably had been achieved. Because it is known from maximal infusion experiments that further expansion of the distal triglyceride pool is nevertheless possible, it follows that another, subsequent pool was saturated during low-rate infusion.

The differences found in proximal and distal distributions of mucosal ^{14}C-labeled lipid (see Table 2), and in particular the quite considerable differences that must have occurred in the triglyceride pool sizes of individual proximal and distal mucosal cells, do not affect the conclusions regarding the regional differences in transmucosal lipid transport rates so long as only the periods of first-order kinetics are considered. In a first-order process (when the pool is not saturated), the fractional output rate is independent of the pool size. Hence, the degree of filling of individual mucosal cells during the first-order decay periods, which were used to calculate $t_{1/2}$ and b', may be safely ignored so long as uptake was complete and only mucosa from the test regions was engaged in triglyceride transport. However, it is clear that during the final hour of low-rate infusion the efficiency of triglyceride output declined in distal intestine while fat accumulation in the intestinal wall continued to increase. If a limit to the amount of triglyceride that can be stored in distal mucosal cells while awaiting incorporation into chylomicrons also exists, as suggested by maximal infusion experiments, this implies that ultimately lipid uptake from the lumen must cease in distal intestine. It should be emphasized that no such potential mechanism applies to proximal intestine, where luminal factors such as diffusion through the unstirred water layer adjacent to the mucosal membrane must control the maximum achievable rate of lymphatic transport.

In summary, we propose that luminal uptake is rate limiting for lipid transmucosal transport in the normal proximal intestine of the rat, whereas in the distal intestine transport is limited primarily by the rate of chylomicron synthesis and release. The present data alone do not imply that individual distal mucosal cells are unable to secrete triglyceride at the same maximum rate as individual proximal mucosal cells, although previous experiments of maximal absorption suggest that such cellular differences in transmucosal lipid transport capacity might be present. Definitive studies of transport kinetics in individual cells are not possible in vivo, however. Moreover, the finding that proximal intestine differs from distal intestine as a whole with respect to chylomicron secretion is likely to be of greater relevance to the organism. Preliminary analysis of chylomicrons synthesized by proximal and distal intestine showed that these also differed structurally. Distal chylomicrons were larger on the average, had significantly higher triglyceride:phospholipid and protein:phospholipid ratios, and had a lower proportion of esterified:unesterified cholesterol. It appears that distal rat intestine can absorb and transport fat quite efficiently, but the result is a fundamentally different particle from that which is normally transported by proximal intestine.

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