Absorption and retinol equivalence of β-carotene in humans is influenced by dietary vitamin A intake

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Abstract The effect of vitamin A supplements on metabolic behavior of an oral tracer dose of [14C]β-carotene was investigated in a longitudinal test-retest design in two adults. For the test, each subject ingested 1 nmol of [14C]β-carotene (100 nCi) in an emulsified olive oil-banana drink. Total urine and stool were collected for up to 30 days; concentration-time patterns of [14C]β-carotene, [14C]retinyl esters, and [14C]retinol were determined for 46 days. On Day 53, the subjects were placed on a daily vitamin A supplement (10,000 IU/day), and a second dose of [14C]β-carotene (retest) was given on Day 74. All [14C] determinations were made using accelerator mass spectrometry. In both subjects, the vitamin A supplementation was associated with three main effects: 1) increased apparent absorption: test versus retest values rose from 57% to 74% (Subject 1) and from 52% to 75% (Subject 2); 2) an ~10-fold reduction in urinary excretion; and 3) a lower ratio of labeled retinyl ester/β-carotene concentrations in the absorptive phase. The molar vitamin A value of the dose for the test was 0.62 mol (Subject 1) and 0.54 mol (Subject 2) vitamin A to 1 mol β-carotene. Respective values for the retest were 0.85 and 0.74. These results show that while less cleavage of β-carotene occurred due to vitamin A supplementation, higher absorption resulted in larger molar vitamin A values.—Lemke, S. L., S. R. Dueker, J. R. Follett, Y. Lin, C. Carkeet, B. A. Buchholz, J. S. Vogel, and A. J. Clifford. Absorption and retinol equivalence of β-carotene in humans is influenced by dietary vitamin A intake. J. Lipid Res. 2003. 44: 1591–1600.

Supplementary key words  accelerator mass spectrometry • isotope • kinetic

β-Carotene is a commonly consumed plant pigment (polyene) that is a biological antioxidant and a nutritional precursor of vitamin A. Within the intestine, β-carotene can be cleaved (Scheme 1) to yield two molecules of vitamin A (retinol) (1). A large percentage of consumed carotenote is absorbed intact, metabolized to vitamin A and other products of uncertain vitamin A value, or excreted (2). However, for reasons that are not well defined, β-carotene is a relatively poor source of vitamin A (3). Some of the variability of the reported vitamin A activity of β-carotene under controlled conditions can be attributed to both dose formulation and administration and the absorption and metabolism of the consumer, presumably controlled by genetic traits.

However, outside of a controlled experimental setting, a number of other factors may also affect β-carotene absorption and vitamin A value, including the type and quantity of dietary fat (4, 5), competition among coconsumed carotenoids (6), the plant or food matrix of incorporation (5), and the extent of mucosal metabolism (7). Determining the contribution of each factor to the vitamin A value is key to understanding the individual response.

The importance of β-carotene as a primary vitamin A source in less-developed regions suggests that in these individuals, status may be an important factor (8). In Filipino children of low or marginal vitamin A stores, the bioconversion of plant carotenoids to vitamin A varied inversely with vitamin A status (9). These findings were strengthened by the use of isotope dilution methods for the assessment of body stores rather than the measurement of circulating retinol concentrations (10). A molecular basis for the observed relationship is suggested in rat studies that report increased activity of the main carotenoid cleavage enzyme, β,β-carotene 15,15-monooxygenase, in intestinal homogenates of vitamin A-deficient animals (11–14). Moreover, it has been observed that large doses of β-carotene do not result in vitamin A toxicity (15), suggesting homeostatic control of bioconversion or saturation of the cleavage enzyme.

Using functional indicators, the earliest investigations into the vitamin A value of β-carotene estimated that between 2 µg to 4 µg of β-carotene were needed to have the same biological efficacy (i.e., vitamin A activity) as 1 µg of...
retinol (16–18). In terms of molar vitamin A value, this is equivalent to 0.47 mol to 0.94 mol retinol formed from 1 mol β-carotene. More recently, stable isotope tracing has been applied to β-carotene conversion studies [for review see ref. (19)]. As an example, a study in one woman taking a pharmacological (126 mg) and physiological (6 mg) dose of deuterium-labeled β-carotene reported that vitamin A activity was highly dose dependent, resulting in molar vitamin A values of 0.034 mol and 0.5 mol retinol per mol β-carotene, respectively (20).

A survey of other quantitative efforts with stable isotopes of carotene shows doses that range from 6 mg to 40 mg (19). One concern with milligram-sized doses is that they may be saturating and exceed the average transport and cleavage capacity of the intestine. Indeed, During et al. (21) estimated that the average adult intestine can maximally cleave ∼2.5 mg of β-carotene/day, and this value would argue against the use of milligram-sized doses, particularly when given in a single bolus. To circumvent saturation conditions when using stable isotopes, van LIESHOUT et al. (22) proposed a multiple dosing design in which microgram-sized doses of carbon-13-labeled β-carotene and retinyl palmitate are consumed for 3 weeks. At the end of the dose period, the relative enrichment of the two forms of isotopically labeled retinol (derived from β-carotene and preformed vitamin A) are used to estimate the relative vitamin A value of the carotene component. By this method, a molar vitamin A value for β-carotene of 0.75 was determined in Indonesian children.

Kinetic studies are facilitated by use of isotopically labeled analogs (tracer) of the natural dietary form (tracere). Whereas radioisotopes such as 14C or tritium were once customary (23, 24), stable isotopes are now more common (19). The motivation for the shift, however, is mainly apprehension over the use of large radiative doses (25) and not the inducement of a superior analytic method. Recently, we (26) utilized accelerator mass spectrometry (AMS) detection of a [14C]β-carotene tracer. AMS is an isotope ratio instrument that measures 14C/12C ratios to parts per quadrillion (10−15), quantifying labeled biochemicals to attomolar (10−18) levels in milligram-sized samples (25, 27). Extremely low detection limits allowed the use of low, safe radiation doses, and small sample sizes permitted a high density of sampling. Radiation exposure was comparable to that incurred naturally from cosmic rays in a single day (25). From the analysis of total excreta, dose absorption and rates of elimination were determined. Using this approach with one male subject, a molar vitamin A value of 0.53 was calculated for β-carotene. Long-term kinetics in plasma to 209 days was also possible because of the low natural abundance of 14C and high sensitivity of the AMS instrument.

The aim of the present study was to determine the effect of vitamin A supplementation on the absorption and retinol equivalence of β-carotene. We studied the metabolic fate of physiologic (536 ng) oral doses of [14C]β-carotene in two female volunteers before and after a 21 day vitamin A supplementation period. Total 14C was measured in plasma, urine, and stool to assess total dose absorption and excretion rates. The time course of labeled retinyl esters, retinol, and parent β-carotene were determined in plasma using liquid chromatographic separation followed by 14C-AMS analysis.

MATERIALS AND METHODS

Chemicals

All chemicals were checked for 14C content by AMS prior to use. Tributryin (glycerol tributyrate) was purchased from ICN Pharmaceuticals (Costa Mesa, CA) and dissolved in methanol from Sigma (St. Louis, MO). β-Carotene and all-trans retinol standards were obtained from Sigma. All solvents and other chemicals, unless otherwise noted, were obtained from Fisher Scientific (Santa Clara, CA). The all-trans-[14C]β-carotene was a gift from Hoffmann-La Roche (Basel, Switzerland). Olive oil, skim milk, sugar, bananas, and other groceries were from a local supermarket.

Dose preparation

Synthetic all-trans-[10,10′,11,11′-14C]β-carotene was purified by reversed-phase high performance liquid chromatography (RP-HPLC) as previously described (26). The purified dose was suspended in 1 ml absolute ethanol. Radiochemical purity was >99%. all-trans-β-Carotene accounted for >90% of the dose, with the remaining being associated with cis isomers. Specific activity was 98.8 mCi/mmol. The dose in ethanol was added to an emulsion (shake) of the following composition: olive oil (0.5 g/kg body weight), 300 g of fresh banana, 100 mL skim milk, and 12.6 g sucrose were blended. About half of the shake was transferred to a plastic cup, the all-trans-[14C]β-carotene dose (in ethanol) was placed on top, and the remaining half of the shake layered atop the dose. The layers were stirred gently and consumed by the volunteer.

Subjects and experimental design

Subjects 1 and 2 were healthy women aged 41 and 43 years with a BMI of 23.6 and 26.7, respectively. Their blood lipid levels were normal. Subjects were administered a 1 year semi-food frequency questionnaire (DIETSYS-NCI Dietary Analysis System, version 3.7c). Typical daily consumption values of vitamin A and β-carotene for Subject 1 was 4,947 IU [1,484 retinol equivalents (REs)] and 1,074 μg of β-carotene. Respective intake values for Subject 2 were 3,416 IU (1,025 REs) and 1,310 μg. Subjects were

Scheme 1. The proposed central cleavage (solid line) and the eccentric cleavage (dashed line) pathways. [Reprinted from Wang et al. (50).]
instructed to avoid foods rich in vitamin A or provitamin A carotenoids for 1 week prior to the study but to otherwise maintain their usual dietary habits. They were asked to keep a complete record of food intake for 2 weeks after dosing.

The experiment was designed to incorporate a test and retest period (Fig. 1). Subjects began complete fecal and urine collection 24 h in advance of the dose and continued complete 24 h collections until Day 16 and Day 30, respectively. On the day of dose administration, subjects were fitted with an intravenous catheter in a forearm vein. Blood was drawn into 7 ml tubes containing EDTA. A baseline blood sample was drawn (7 AM) and the dose consumed. Blood samples were drawn at 1, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5, 8, 8.5, 9, 9.5, 10, 10, 11, 12, 13, 14, 24, and 36 h post dosing. Blood samples were also collected between 8 AM and 8:30 AM on days 2, 3, 4, 5, 6, 9, 11, 13, 18, 25, 32, 39, and 46 in the fasted state.

Meals were controlled for time and content on the dose administration day. Lunch was served at 5.5 h postdosing and consisted of a frozen dinner (Enchiladas, Amy’s Kitchen, Petaluma, CA), a blueberry bagel with jelly, 1 apple and 1 banana, and a large chocolate chunk cookie (Pepperidge Farm). Dinner was served 10.5 h post dose and consisted of a frozen dinner (Chinese Stir Fry, Amy’s Kitchen) plus the bagel and fruit taken for lunch. Each meal was selected to deliver 20 g of fat in ~600 calories; lunch contained 300 µg REs and dinner 700 µg REs.

The administration of a second [14C]-β-carotene dose marked the beginning of the retest period at Day 74. Three weeks prior to the start of the retest (Day 74), subjects began consuming 10,000 IU (3,000 µg REs) of vitamin A supplement daily (as retinyl palmitate, GNC, Pittsburgh, PA) and continued at that level until 2 weeks after the retest dose administration. The supplement was not consumed on the day the retest dose was administered. Blood samples were also collected on the day of the retest dose administration, subjects were fitted with an intravenous catheter in a forearm vein. A baseline blood sample was drawn (7 AM) and the dose consumed. Blood samples were drawn at 1, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5, 8, 8.5, 9, 9.5, 10, 10, 11, 12, 13, 14, 24, and 36 h post dosing. Blood samples were also collected between 8 AM and 8:30 AM on days 2, 3, 4, 5, 6, 9, 11, 13, 18, 25, 32, 39, and 46 in the fasted state.

Sample preparation

Plasma was separated by centrifugation and stored at −80°C. Complete urine samples were collected in tared 3 l plastic amber urine collection containers (Fisher). The urine was prepared for 14C analysis by diluting a 1 ml aliquot with 9 ml of water. A 100 µl aliquot of the dilution was transferred to a quartz combustion vial for 14C determinations. Stool samples were collected in 4 ml collection bags (Fisher Scientific). Stool weights were recorded, and a volume equal to five times the sample stool mass of 1:1 2-propanol-M K OH was added directly to the bag. The mixture then was dispersed with a Stomacher 3500 laboratory blender (Brinkmann, Westbury, NY) for 2 min at the high setting. Samples were heated in a water bath for 2 h at 70°C and redispersed on the Stomacher for 2 min. This heating-mixing cycle was repeated once more. A 40 µl aliquot was transferred to a 50 ml polypropylene tube containing 25 g of glass beads (6 mm; Fisher Scientific). The tube was capped and shaken by wrist-action (Model 75; Burrell Scientific, Pittsburgh, PA) for 6 h at maximum speed. One milliliter of the homogenate was diluted with 9 ml:1 1:2-propanol-M K OH, and a 100 µl aliquot was transferred to a quartz combustion vial for AMS analysis. Total carbons for plasma, urine, and stool samples were determined by the DUMAS method (28).

Analyte determinations

Eluent fractions of the HPLC corresponding to retinol or β-carotene were collected in quartz combustion vials, and 14C was measured by AMS. Because retinyl esters and β-carotene comigrated on our system, two chromatographic separations were needed. In the first analysis, free retinol was determined. In the second run, β-carotene and retinol were determined after saponification of the plasma extract; the saponification step effected the conversion of all retinyl esters to their common moiety, retinol. Final retinyl ester concentrations were determined by the difference in plasma retinol pre and post saponification. The procedure is as follows. Plasma (200 µl) was denatured with 400 µl ethanol and extracted with 3 × 1 ml of hexane, which was pooled. The extracts were dried under nitrogen gas, and the sam-

![Fig. 1](https://example.com/f1.png)  
**Fig. 1.** Experimental design and time line. The experiment was designed to incorporate a test and retest period. In the test period, subjects began complete fecal and urine collection 24 h in advance of the dose and continued complete 24 h collections until Day 16 and Day 30, respectively. On the day of dose administration, subjects were fitted with an intravenous catheter in a forearm vein. Blood was drawn into 7 ml tubes containing EDTA. A baseline blood sample was drawn (7 AM) and the dose consumed. Blood samples were drawn at 1, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5, 8, 8.5, 9, 9.5, 10, 10, 11, 12, 13, 14, 24, and 36 h post dosing. Blood samples were also collected between 8 AM and 8:30 AM on days 2, 3, 4, 5, 6, 9, 11, 13, 18, 25, 32, 39, and 46 in the fasted state.

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concentrations were calculated by adjusting for saponification. The whole procedure was a minimum of 92%. [14C]retinyl ester was recovered after saponification (using retinyl palmitate as the test compound) was 90% in cumulative retinol recovery was 81%. Retinyl ester extraction recovery was 65% Solvent B (1:1 CH3CN-MeCl2 0.02% ammonium acetate), followed by 1–4 min linear ramp to 100% Solvent B at 0.5 ml/min; hold until 10 min.

AMS analysis

C14 determinations were made at the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory. Mean differences in β-carotene concentrations between test and retest periods were significant (P < 0.05). Retinol concentrations did not differ significantly. A summary of fecal and urinary excretion data is displayed in Fig. 2 and Table 1. Subject 1 absorbed 57% of the test dose, although fecal excretion extended over 6 days. Fecal elimination shortened to 4 days under

RESULTS

Mean plasma retinol and β-carotene concentrations are summarized in Table 1. Vitamin A value and kinetic parameters after administration of 1.0 nmol oral dose [14C]β-carotene

<table>
<thead>
<tr>
<th></th>
<th>Subject 1</th>
<th>Subject 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test</td>
<td>Retest</td>
</tr>
<tr>
<td>Plasma retinol</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (SD)</td>
<td>1.53 (0.09)</td>
<td>1.58 (0.16)</td>
</tr>
<tr>
<td>Plasma β-carotene</td>
<td>0.28 (0.07)</td>
<td>0.43 (0.05)</td>
</tr>
<tr>
<td>Absorbed dose</td>
<td>57</td>
<td>74</td>
</tr>
<tr>
<td>Cumulative dose excreted in stool (%)</td>
<td>47</td>
<td>28</td>
</tr>
<tr>
<td>Absorbed dose excreted in stool (%)</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>Absorbed dose excreted in urine (%)</td>
<td>35</td>
<td>4</td>
</tr>
<tr>
<td>Absorbed dose excreted in urine from 0–72 h (%)</td>
<td>31</td>
<td>3</td>
</tr>
<tr>
<td>Urinary excretion rate 5–30 days (% absorbed dose/d)</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Absorbed dose stool excretion rate % absorbed dose/d</td>
<td>0.046</td>
<td>0.032</td>
</tr>
<tr>
<td>Urinary/stool excretion rate ratio</td>
<td>2.21</td>
<td>0.88</td>
</tr>
<tr>
<td>AUC0–5/14C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Retinyl esters</td>
<td>3.976</td>
<td>15.018</td>
</tr>
<tr>
<td>β-Carotene</td>
<td>1.666</td>
<td>6.787</td>
</tr>
<tr>
<td>Retinol</td>
<td>743</td>
<td>1.054</td>
</tr>
<tr>
<td>Retinyl esters/β-carotene</td>
<td>2.39</td>
<td>2.21</td>
</tr>
<tr>
<td>% Recovery in components (SUM/14C)</td>
<td>28</td>
<td>32</td>
</tr>
<tr>
<td>Vitamin A value</td>
<td>0.62</td>
<td>0.85</td>
</tr>
<tr>
<td>Half-life (t1/2) retinol (d)</td>
<td>140</td>
<td>243</td>
</tr>
<tr>
<td>Half-life (t1/2) β-carotene (d)</td>
<td>29</td>
<td>35</td>
</tr>
<tr>
<td>Turnover time β-carotene (d)</td>
<td>29</td>
<td>51</td>
</tr>
</tbody>
</table>

* Mean (±SD), sampling of time points at 0, 0.27, 0.61, 1.0, 1.5, 2.0, 4.0, and 6.0 days postdosing.
  † Significantly different at P < 0.05.
  ‡ First 5 days for Subject 1; 2.5 days for Subject 2.
  § Percent of total dose over 17 days of stool collection.
  ¶ Urine collections occurred over 6 days.
retest with an increased absorption to 74%. Subject 2 displayed a more rapid excretion of the nonabsorbed [14C]-β-carotene. In the test period, 48% was lost (52% absorbed) in two collections, while in the retest period, 25% was lost (75% absorbed) in two collections. [14C] signal was present in the 0–6 h urine collection in both subjects and in both test periods. The largest single output occurred within 48 h in all cases. Urinary excretion dominated fecal excretion after the absorption phase, contrary to a previous report in a male subject (26). The rate of urinary [14C] excretion was 2.2 and 2.4 times that of stool for Subjects 1 and 2, respectively, in the test period. Output of the absorbed dose via urine over the first 30 days post dosing was much smaller in the retest period than in the test period in both subjects. Specifically, absorbed dose excreted in the urine of Subject 1 was 31% during the test and 3% during the retest; Subject 2 excreted 26% during the test and 3% during the retest. After dose equilibration at Day 5, the rate of urine loss was low for both subjects and in both periods; as a result, differences in total excretion were largely attributable to the early time points.

Plasma β-carotene and retinyl ester concentration before and after supplementation for the first 50 h are shown in Fig. 3. In test absorptive period (0–10 h), analyte concentrations rose to a first maximum centered at 8 h for both subjects, passing through a small shoulder at the leading edge of main peak. A similar structure for both subjects and both analytes was observed in the retest with the obvious addition of a well-resolved first peak (shoulder peak in the test). Concentrations for the two analytes within both subjects moved in parallel, suggesting a single transporter for both analytes. Concentrations of circulating β-carotene were persistent and equivalent at ~2,000–4,000 attomolar for both subjects in the distributive period (10–24 h) of both the test and retest. Subject 2 doubled the circulating β-carotene in the retest phase over the test phase, however. Subject 1 displayed a strong resurgence in retinyl ester concentration that was muted after supplementation and decayed away in both instances between 15 h and 50 h. Subject 2 displayed a very attenuated rise in retinyl esters in the retest that was not present in the test.

The integrated ratio of retinyl ester/β-carotene from 0 h to 5 h (AUC0–5) estimates the vitamin A value of β-carotene (Table 1). AUCs tabulated over longer periods could be influenced by postintestinal actions and therefore are not viewed as valid estimators of intestinal cleavage. The derived ratios were 2.39 and 2.73 for Subjects 1 and 2, respectively, during the test period. Retest values were 2.21 and 1.93 for Subjects 1 and 2, respectively. Assuming cen-
art cleavage of β-carotene and adjusting for dose absorption from the stool information, the conversion ratio (vitamin A value) for the test was 0.62 and 0.54 mol vitamin A to 1 mol β-carotene for Subjects 1 and 2, rising to 0.85 and 0.74 mol vitamin A to 1 mol β-carotene in the retest. (A value of 1, interpreted as meaning that 1 mol of ingested β-carotene, is equivalent to 1 mol of preformed vitamin A.) Another way to examine the bioconversion is to plot the concentration ratio of retinyl ester/β-carotene at discrete time points (Fig. 4). The data displayed an overall depletion of retinyl esters relative to β-carotene concentrations with time, except for apparent influxes coincident with the times of second and third meals (indicated by arrows). Ratios in the test period were consistently higher than retest ratios for both subjects.

The time courses for the appearance and disappearance of [14C]retinol in plasma over 9 days following dosing is presented in Fig. 5. In all cases, the concentration rose to a single peak (albeit broad for Subject 1 retest), with a maximum concentration of ∼24 h for Subject 1, and much earlier at ∼12 h for Subject 2. The absence of multiple peaking is consistent with the controlled release of retinol with retinol binding protein (RBP) following hepatic uptake of retinyl esters.

Figure 6 shows the fraction of the total plasma 14C concentration that is comprised of the sum of retinol, retinyl esters, and β-carotene as functions of subject, vitamin supplementation, and time. Integrated AUCs have the effect of dampening fluctuations due to meals and other effects, facilitating observation of general trends. The three assayed components accounted for only 60–70% of the isotopic label throughout the distribution and elimination phases of both subjects, with and without vitamin A supplementation. A slight downward trend was apparent in Subject 1. In the absorptive phase, the main effect of supplementation was improved recovery of the components; recoveries prior to supplementation were surprisingly low, ranging from near zero (Subject 2) to 30% (Subject 1) in the first 6 h; similar retest values ranged were ≥90% and ≥75% in Subject 1 and 2, respectively.

**Fig. 4.** Concentration ratio of retinyl ester/β-carotene at discrete time points. In general, the data displayed a negative slope in response to depletion of retinyl ester concentrations relative to β-carotene concentrations. Solid arrows indicate timing for second and third meals. Ratios in the test period were consistently higher than retest ratios for both subjects for 10 h.

**Fig. 5.** Time course line plots of [14C]retinol in plasma from 0–100 h. Unlike β-carotene and retinyl esters, retinol concentrations rose to a single peak.

**Fig. 6.** The fraction of the total plasma 14C activity accounted for in the main analytes, retinol, retinyl esters, and β-carotene as a function of subject, vitamin supplementation, and time. The three assayed components accounted for only 60–70% of the isotopic label throughout the distribution and elimination phases of both subjects, with and without vitamin A supplementation.
DISCUSSION

β-Carotene is thought to diffuse from mixed micelles in the small intestine through the unstirred water layer and into the enterocyte before entering the lymph with chylomicrons. The passive nature of this process does not suggest that vitamin A supplementation would result in uptake regulation of β-carotene. In this study, however, we observed that supplemental retinyl palmitate (retest) was associated with a decrease in the recovery of the 14C label in the first several stool collections (Fig. 2; Table 1). We do not know the basis of the effect; however, vitamin A is important in controlling epithelial health and gut integrity (30–32), and changes in the gut in response to supplementation in our subjects may provide one explanation for the observed effects. A second explanation has to do with biliary excretion of the 14C label. Using our balance technique, an enhancement in the biliary excretion of absorbed β-carotene and its metabolites could give the appearance of decreased absorption by increasing the output of 14C in the stool. In the case of lipophilic compounds, biliary excretion is largely a result of a compound being metabolized in the gut wall prior to transportation to the liver via the hepatic portal vein (33). Elimination is then distributed between the bile and the urine. Our urine data indicate that a substantial portion of the dose was eliminated in the urine in the unsupplemented subjects (Fig. 2); therefore, it is reasonable to assume that a fraction of the dose was cleared in the bile as well (34). Regardless of which theory is correct, it is clear that supplementation altered the bioavailability of the carotene dose, although the balance between uptake and elimination cannot be fully explained on the basis of stool data. An understanding of the identity of the urinary and stool products may help resolve this issue. Further studies are needed to better understand the mechanism governing this effect.

The primary objective of the current study was to investigate the effect of dietary vitamin A on the vitamin A value of β-carotene. In this limited sample set, we have seen that supplementation was associated with a higher molar vitamin A value. In accord with the higher dose absorption, the absolute AUCs for both β-carotene and retinyl esters increased for both subjects. We focused on retinyl esters and β-carotene because plasma retinol is not of intestinal origin. The fraction of the dose converted to retinyl esters, however, was lower in both subjects, suggesting that a smaller percentage of absorbed β-carotene molecules were actually cleaved in the retest. As vitamin A value is the product of absorption and the fraction of absorbed β-carotene that is cleaved to vitamin A, the larger absorption in the retest is responsible for the higher molar vitamin A value in these studies. Determined molar ratios ranged from 0.54 to 0.85, which are comparable to values obtained by methods that used functional indicators as end points as well as some stable isotope methods (19). Intracellularly, the activity of the principal known carotenoid cleavage enzyme β, β-carotene 15,15'-monooxygenase may serve as a key regulatory point (12, 35, 36) in the bioconversion. In the rat, vitamin A deficiency can increase intestinal cleavage activity, while excess vitamin A or β-carotene is inhibitory (36). Our results suggest absorption can be more important than cleavage capacity in determining β-carotene’s vitamin A value.

We determined the metabolic behavior of 14C as well as the major analytes [14C]β-carotene, [14C]retinyl esters, and [14C]retinol in plasma. The concentration profile for labeled retinyl esters and β-carotene (Fig. 3) showed two maxima in the absorptive phase for both subjects, with a larger and more resolved first maxima in the retest; retest β-carotene and retinyl ester AUCs were, on average, 3- to 4-fold greater in magnitude than corresponding test period AUCs (Table 1). In contrast, 14C AUCs were essentially unchanged in Subject 1, and were ~50% larger in Subject 2. This discrepancy between the 14C recovered in the analytes versus total 14C activity suggests that substantial label resides with other metabolites. The plots in Fig. 6 illustrate the magnitude of this effect over time. Values below 1 indicate the degree to which metabolites other than the main components constitute the incoming dose. Prior to supplementation, only a small fraction of the label was recovered as the main component in the early absorptive period. The effect lessened with time, and at later periods, ~50–70% of the label is present in plasma as the main metabolites. The patterns were markedly different in response to supplementation; supplementation increased the recovery of the label in the main components. This may suggest a sparing effect of vitamin A supplementation on the β-carotene and vitamin A utilization.

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Presystemic reactions within the intestinal mucosal wall dictate the early metabolite profile. Although there is limited human information on this subject, cytosolic extracts of human enterocytes and intact Caco-2 cells can metabolize retinol to retinoic acids and oxygenated end products of retinoic acid metabolism (7). Studies in the ferret have reported “substantial” conversion of β-carotene to polar end products that include retinoic acids and asymmetric cleavage products, i.e., apo-carotenoids (37, 38). Similar metabolism in our subjects might explain the poor recoveries of label in the main metabolites. It can be supposed that supplemental vitamin A in the retest satisfied immediate vitamin A needs in the enterocytes, therefore directing metabolism toward storage products (retinyl esters). We previously identified 13-α-trans retinoic acid as a blood metabolite of [14C]β-carotene (26). Moreover, RP-HPLC analysis of plasma (data not shown) revealed one unknown component that has the chromatographic character of the neutral oxidation product of β-carotene (epoxide?).

The poor plasma recoveries of 14C in the main metabolites coincided with large losses of the absorbed dose in the first 0–6 h urine: 0–6 h test urines contained 8% and 14% of the absorbed dose in Subjects 1 and 2, respectively. Conversely, higher plasma recoveries after supplementation coincided with marked reductions in 14C in the urine (Table 1; Fig. 7). Thus, intestinal metabolism (test) would appear to generate products that are poorly retained and readily eliminated into the urine. Indeed, β-carotene, retinyl esters, and retinol are not found in normal urine; many of the metabolites identified to date are chain-shortened, oxidized, conjugated products (39, 40). Vitamin A supplementation was also associated with a reduction in the long-term output of label in urine, suggestive of modifications in postabsorptive turnover.

The plot of retinyl ester/β-carotene concentrations in the absorption phase displayed a negative slope, consistent with differential postabsorptive handling of the compounds. The descent in the ratio was marked by several rises, most visibly in the test period, which were coincident with the meals. Fielding et al. (41) also demonstrated the importance of the second meal effect. They fed a high-fat breakfast and lunch meals was present to shuttle more [14C] retinyl acetate in plasma with lipoproteins (47, 48), and our data suggest that humans may have this capacity as well. An analysis of the apoB protein forms (intestinal vs. hepatic) associated with latent rises would help resolve this issue.

The time course of retinol in the plasma was very different for both subjects from retinyl esters and β-carotene, consistent with the controlled release of retinol with RBP following hepatic uptake of retinyl esters. There was no evidence for the absorption of free retinol from the intestine in the form of an early concentration peak, contrary to observations by us (26). It is noteworthy that the late maxima in Subject 1 (relative to Subject 2) were preceded by the large (test) and moderate (retest) retinyl esters rises past 10 h, consistent with a precursor-product relationship. The long-term kinetics of β-carotene and retinol were also calculated in the retest and were found to be 140 days and 243 days for retinol and 20 days and 35 days for β-carotene. This is generally consistent with an earlier study utilizing [14C] retinyl acetate that reported mean t1/2s of 154 days with a range of 75 days to 241 days (18). β-Caro-
tene half-lives have been reported as less than 12 days (49) and 40 days (26). The scarcity of data on elimination of these bioactive compounds necessitates the collection of larger data pools from diverse cross sections of the population.

In conclusion, we have shown that vitamin A supplementation at levels moderately above recommended daily allowance has effects on β-carotene metabolism that are readily detected when using AMS detection. Notable effects included a reduction in the postprandial ratio of retinyl esters to β-carotene with a concomitant increase in total dose absorption. Increased dose absorption resulted in a higher overall vitamin A value for β-carotene in response to supplementation, which was accentuated by attenuation in early metabolism of the dose to urinary end products.

The high degree of parallelism between the [14C]retinyl esters and [14C]β-carotene in our studies suggests that a tightly linked or single mechanism controls the incorporation of β-carotene and the retinyl esters derived from it into nascent chylomicrons (43). This finding is at variance with ferret intestinal perfusion studies, which found β-carotene was released more slowly than its retinoid metabolites in the lymphatics (44). Subject 1 displayed a second interesting phenomenon, which we had originally observed in a single male subject (26); that is, the latent rise in retinyl esters that peaked at 18 h. The secondary meal effect has been examined above. A second consideration for the rise in Subject 1 (and to a lesser extent in both subjects and both test periods) is resecretion of retinyl esters from the liver with hepatic lipoproteins. The occurrence of such a pathway is deemed important since some of the anticancer effects of vitamin A have been attributed to circulating retinyl esters (45). Indeed, ~5–10% of circulating vitamin A in fasting plasma is in the form of retinyl esters (46), and while some of the retinyl esters may be associated with traces of chylomicra not removed by the liver, the magnitude of the rise in our experiments would suggest a new input. Dogs, ferrets, and cats are reported to transport retinyl esters in plasma with lipoproteins (47, 48), and our data suggest that humans may have this capacity as well. An analysis of the apoB protein forms (intestinal vs. hepatic) associated with latent rises would help resolve this issue.
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