Amount and fate of egg protein escaping assimilation in the small intestine of humans

PIETER EVENEPOEL, DIRK CLAUS, BENNY GEYPENS, MARTIN HIELE, KAREN GEBOES, PAUL RUTGEEERTS, AND YVO GHOOSS
Department of Medicine, Division of Gastroenterology and Gastrointestinal Research Centre, University Hospital Leuven, B-3000 Louvain, Belgium

Amount and fate of egg protein escaping assimilation in the small intestine of humans. Am. J. Physiol. 277 (Gastrointest. Liver Physiol. 40): G935–G943, 1999.—Studies attempting to evaluate protein assimilation in humans have hitherto relied on either ileostomy subjects or intubation techniques. The availability of stable isotope-labeled protein allowed us to determine the amount and fate of dietary protein escaping digestion and absorption in the small intestine of healthy volunteers using noninvasive tracer techniques. Ten healthy volunteers were studied once after ingestion of a cooked test meal, consisting of 25 g of 13C-, 15N-, and 2H-labeled egg protein, and once after ingestion of the same but raw meal. Amounts of 5.73% and 35.10% (P < 0.005) of cooked and raw test meal, respectively, escaped digestion and absorption in the small intestine. A significantly higher percentage of the malabsorbed raw egg protein was recovered in urine as fermentation metabolites. These results 1) confirm that substantial amounts of even easily digestible proteins may escape assimilation in healthy volunteers and 2) further support the hypothesis that the metabolic fate of protein in the colon is affected by the amount of protein made available.

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gastrointestinal complaints and were free of antibiotics or any other medical treatment for at least 3 mo before the start of the study. The study was approved by the Ethical Committee of the University of Leuven, and all subjects gave informed consent.

Experimental Design

The study was conducted over a 21-day period including a 7-day baseline period and two study periods, separated by a washout period of 7 days. Each study period started with the ingestion of the labeled test meal and lasted 3 days. The two study periods were identical, apart from the test meal, which had to be ingested once cooked and once raw. The two consecutive study periods were allocated in a randomized order.

All subjects were studied after an overnight fast of at least 12 h. At 0845 on the first day of the study period, the volunteers ingested the protein test meal together with 200 ml of water within 15 min. No further food was allowed until 1500, when the volunteers consumed a standard bread meal. Drinking of water was permitted from 1200 on.

The experimental design is schematically represented in Fig. 1.

Diet

The volunteers were given no standard diets. However, they were asked to weigh and record all food and drinks taken from 3 days before until the end of each study period. These data were analyzed using a computer program to obtain energy and nutrient intake results (Nederlands voedingsstoffenbestand 1989–90, Voorlichtingsbureau voor de voeding, Den Haag, The Netherlands).

Test Meal

The protein test meal consisted of 100 g of egg white (i.e., 11 g of egg white protein) labeled with 15N, 100 g of egg white labeled with L-[1-13C]leucine and L-[ring-H2]tyrosine, and the yolk of one egg. Five microcuries [3H]polyethylene glycol ([3H]PEG) 4000 were added to the test meal as a radiolabeled transit marker. All the constituents of the test meal were mixed before ingestion. Total caloric content of the test meal was 150 kcal (25 g of protein, 5.56 g of fat, and a negligible amount of carbohydrates).

The methodology for obtaining large amounts of highly enriched egg proteins labeled with stable isotopes has been described elsewhere (9). Briefly, 15N- or 13C-labeled proteins were produced by giving laying hens free access to a food containing 20% of the (National Research Council required) phenylalanine content as free L-[ring-H2]phenylalanine (98 mol%, Euriso-top). Due to hydroxylation of L-[ring-H2]phenylalanine by the hen, both L-[ring-H2]phenylalanine and L-[ring-H4]tyrosine are incorporated in the egg protein. The L-[ring-H2]tyrosine content of the egg protein was determined by gas chromatography-mass spectrometry (GCQ, Finnigan, San J osé, CA) (14).

Sample Collection

Breath samples were collected in exetainers (Europa Scientific) before ingestion of the meal, every 15 min for the first 6 h, and every 30 min up to 9 h after ingestion of the test meal. During each study period, urine was collected in plastic bottles for the following periods: 0–3 h, 3–6 h, 6–9 h, 9–24 h, 24–48 h, 48–72 h. Moreover, a 24-h urine collection was obtained the day preceding each study period. Neomycin was added to the plastic containers used for the collections to prevent bacterial growth. After measurement of the volume, samples were taken and stored at −20°C until analysis.

All stools voided during each of the study periods were collected as well. Date and time of voiding of stools were noted in a diary. The stools were frozen immediately after voiding and stored at −20°C until analysis.

Analytical Procedures and Calculations

Breath samples. The breath samples were analyzed for 13C content by means of a continuous-flow isotope ratio mass spectrometer (ABCA, Europa Scientific). The δ values given by isotope ratio mass spectrometry were converted to percentage of 13C recovery per hour of the initial amount administered (%dose 13C/h) according to calculations previously described in detail (8, 15).

Cumulative percentages of recovered label (cumulative %dose 13C) were calculated by means of the trapezoidal rule. From these data, the following parameters of protein assimilation were derived: the maximum percentage of administered dose of 13C excreted per hour and the cumulative percentage of administered dose of 13C recovered in breath over 6 h.

Fecal samples. After thawing, the stool samples were weighed and homogenized for each day of collection. Samples of known weight were taken and freeze-dried. The dried material was weighed, and aliquots were taken for the analysis of total nitrogen content, 15N enrichment, and [3H]PEG 4000 content.

The [3H]PEG 4000 content was measured by the oxidation method (Packard sample oxidizer, model 306, Packard Instrument, Downers Grove, IL), with subsequent liquid scintillation counting (model 2450, Packard Instrument) and correction for quenching. Results were expressed in cumulative percentage of the administered dose of 3H recovered over 72 h (further referred to as %dose [3H]PEG 4000).

Total nitrogen content and 15N enrichment were determined using a continuous flow elemental analyzer-isotope ratio mass spectrometer (ANCA-2020, Europa Scientific). Briefly, an aliquot of known weight of the lyophilized fecal sample was combusted in the presence of oxygen at 1,000°C. The combustion products thereafter passed through a second
furnace containing copper at 600°C, where excess oxygen was absorbed and nitrogen oxides were reduced to elemental nitrogen. Total nitrogen content was measured by means of a thermal conductivity detector, and 15N enrichment was determined by means of an isotope ratio mass spectrometer, coupled to the combustion unit of the elemental analyzer. The 15N-to-14N isotope ratio of N2 was measured with reference to a calibrated laboratory standard (i.e., a standard ammonium sulfate solution). The values were expressed in atom percent (AP). The intraassay variability of this method, assessed by the coefficient of variation (CV), amounted to 2.6 and 0.3% for total nitrogen content and 15N enrichment, respectively. Results were expressed in percentage of administered dose of 15N recovered per day and in cumulative percentage recovered over 72 h.

The percentage of administered dose of 15N recovered per day was calculated as follows:

%15N dose/day = \frac{\text{mg excess } 15N \text{ administered(b)}}{\text{mg excess } 15N \text{ administered(b)} \times 100}

where a is

\frac{AP_s - 0.368}{100} \times N_{f\text{tot}}

where APs is the measured 15N enrichment of the stools collected on day t, expressed in AP; 0.368 is the natural 15N content of stools, expressed in AP; and Nf\text{tot} is the total nitrogen content of the stools collected on day t, expressed in milligrams.

The calculation of b is

\frac{AP_m - 0.368}{100} \times N_m

where APm is the weighed average 15N enrichment of the test meal (calculated for each test meal separately), expressed in AP, and Nm is the nitrogen content of the protein test meal, i.e., 4,000 mg.

The cumulative percentage of administered dose of 15N recovered in feces over 72 h (further referred to as \(\Sigma_{0h} %\text{dose } 15N_{f\text{adm}}\)) was obtained by summation.

A correction was made for gastrointestinal transit by dividing \(\Sigma_{0h} %\text{dose } 15N_{f\text{adm}}\) by the cumulative percentage of administered dose of 2H4 recovered over 72 h.

\[\sum_{0h} %\text{dose of } 15N_{f\text{adm}} \text{ corrected} = \frac{\sum_{0h} %\text{dose of } 15N_{f\text{adm}}}{\sum_{0h} %\text{dose of } 2H4_{\text{adm}} \text{ corrected}}\]

Urinary samples. Urinary phenol and p-cresol. Phenol, [ring-D4]phenol, p-cresol, and p-[ring-D4]cresol were measured by gas chromatography-ion trap technology as described by Geypens et al. (13). Briefly, 1 ml of urine was diluted with 3 ml of distilled water. Seventy-five microliters of 2,6-dimethylphenol solution (20 mg/100 ml) were added as internal standard. The pH was adjusted to 1 with concentrated H2SO4, and the solution was refluxed for 75 min to hydrolyze the conjugated phenols. After a cooling-down period to ambient temperature, phenols were extracted with 2 ml of diethyl ether. One microliter was injected into the gas chromatography-mass spectrometer (GCQ, Finnigan). After separation on the analytical column, a 25-m × 0.25-mm CP-Sil 5 CB-MS with a film thickness of 0.25 µm (Chrompack, Middelburg, the Netherlands), the phenolic compounds were identified by ion trap technology (ITD 700, Finnigan).

Results for the unlabeled compounds were expressed in amounts excreted per hour and in cumulative amounts excreted over 72 h. Because phenol and p-cresol are quantitatively the major bacterial metabolites of tyrosine, the percentage of administered dose of L-[ring-D4]tyrosine administered expressed in moles (calculated for each test meal separately); and d is the duration of the collection period, expressed in hours.

The percentage of the administered dose of L-[ring-D4]tyrosine recovered per hour as \(\frac{[\text{ring-D4}]\text{phenol rec}}{\text{d} \times \text{L-[ring-D4]tyrosine administered}}\)

where \(\frac{[\text{ring-D4}]\text{phenol rec}}{\text{d} \times \text{L-[ring-D4]tyrosine administered}}\) is the total amount of \(\text{[ring-D4]phenol recovered in the urine fraction of period t (expressed in mol)}\) (the natural urinary content of \(\text{[ring-D4]phenol is zero)}\); L-[ring-D4]tyrosine administered is the amount of L-[ring-D4]tyrosine administered, expressed in moles (calculated for each test meal separately); and d is the duration of the collection period, expressed in hours.

The cumulative percentage of dose of L-[ring-D4]tyrosine administered recovered in urine over 72 h (further referred to as \(\Sigma_{0h} %\text{dose } 2H4_{\text{adm}}\)) was calculated by summation.

The cumulative values were corrected for gastrointestinal transit as follows:

\[\sum_{0h} %\text{dose of } 2H4_{\text{adm}} \text{ corrected} = \frac{\sum_{0h} %\text{dose of } 2H4_{\text{adm}}}{\sum_{0h} %\text{dose of } [\text{ring-D4}]\text{PEG 4000}}\]

Urinary Ntot and 15N. After thawing, a known amount of urine (~15 µl) was absorbed on chromosorb in a tin capsule. Total nitrogen content and 15N enrichment of urine were determined using a continuous flow elemental analyzer isotope ratio mass spectrometer (ANCA-2020, Europa Scientific) as described previously.

Results for 15N were expressed in percentage of the administered dose of 15N recovered per hour and in cumulative percentages recovered over 72 h.

The percentage of administered dose of 15N recovered per hour was calculated as follows:

%15N dose/h = \frac{\text{mg excess } 15N \text{ administered(b)} \times d}{\text{mg excess } 15N \text{ administered(b)} \times 100}

where a is

\frac{AP_s - AP_d - 1}{100} \times N_{u\text{tot}}
where \( AP_s \) is the measured \(^{15}\text{N} \) enrichment of the urine collected in period \( t \), expressed in AP; \( AP_d \) is the \(^{15}\text{N} \) enrichment of the urine of period \( d-1 \), i.e., the natural \(^{15}\text{N} \) content of urine before ingestion of the labeled meal, expressed in AP; and \( N_{\text{u tot}} \) is the total nitrogen content of the urine, collected in period \( t \), expressed in milligrams.

The calculation of \( b \) was as follows

\[
\frac{(AP_m - AP_d)}{100} \times N_m
\]

where \( AP_m \) is the weighted average \(^{15}\text{N} \) enrichment of the test meal, expressed in AP (calculated for each test meal separately), and \( N_m \) is the nitrogen content of the meal, i.e., 4,000 mg.

The cumulative percentage of administered dose of \(^{15}\text{N} \) recovered in urine over 72 h (\( \Sigma^{72\text{h}} \% \text{dose of } ^{15}\text{N}_{\text{adm}} \)) was calculated by summation.

\(^{15}\text{N} \) RETENTION. The percentage of the administered dose of \(^{15}\text{N} \), retained in the body after 72 h, was calculated as follows

\[
\%^{15}\text{N} \text{ retention} = 100 - \left( \Sigma^{72\text{h}} \% \text{dose of } ^{15}\text{N}_{\text{adm}} \text{ corrected} + \Sigma^{72\text{h}} \% \text{dose of } ^{15}\text{N}_{u \text{ adm}} \right)
\]

Statistical Methods

Results are expressed as means ± SE. Statistical analysis was performed with SAS software package. Parameters obtained after ingestion of the raw test meal were pairwise compared with values obtained in the control study using the paired t-test. Correlations were obtained by Pearson's test.

RESULTS

Diet

No significant differences were found between the two study periods either in the intake of protein, fat, and carbohydrates or in the intake of dietary fiber (Table 1).

Breath Tests

Figure 2 shows the mean \(^{13}\text{CO}_2 \) excretion rate in breath after ingestion of the raw and cooked test meal. Differences between both test situations are obvious. The curve obtained after ingestion of the cooked test meal is characterized by a steep ascending slope, a high peak excretion rate, and an initial steep descending slope that smooths down considerably after 6 h. After ingestion of the raw test meal, the \(^{12}\text{CO}_2 \) excretion rate increased more slowly, did not reach the high values obtained after ingestion of the cooked test meal, and remained on a rather constant level after the maximum was reached. The cumulative percent \(^{13}\text{C} \) of administered dose, recovered in breath over time after ingestion of the labeled cooked and raw test meal, is shown in Fig. 3.

Table 2 summarizes the parameters of protein assimilation as derived from the breath test data. Both the maximum percentage of administered dose of \(^{13}\text{C} \) excreted per hour and the cumulative percentage of administered dose of \(^{13}\text{C} \), recovered in breath over 6 h, were significantly higher after ingestion of the cooked test meal compared with the raw test meal.

Feces

Fecal output variables such as wet weight, dry weight, total nitrogen content, and nitrogen density did not differ significantly after ingestion of the cooked and raw test meal (Table 3). The cumulative fecal recovery of \(^{15}\text{N} \), however, was significantly higher after ingestion of the raw test meal \( \Sigma^{72\text{h}} \% \text{dose of } ^{15}\text{N}_{\text{adm}} \text{ corrected: } 4.16 ± 0.27\% \) (cooked) vs. 14.16 ± 1.70\% (raw); \( P < 0.001 \) (Table 4).

Urine

Nitrogen. Figure 4 shows the mean \(^{15}\text{N} \) excretion rate in urine after ingestion of the raw and cooked test meal. Although significant differences in the \(^{15}\text{N} \) excretion rate were noted, the cumulative percentage of adminis-
 registered dose of $^{15}$N, recovered in urine over 72 h was almost the same in both test situations ($\sum_{0h}^{72h}$% dose of $^{15}$Nadm: 35.91 ± 2.12% (cooked) vs. 32.68 ± 1.35% (raw); $P = 0.12$) (Table 3).

Phenols. Figure 5 shows the excretion pattern of phenol, p-cresol, and total phenols in urine. The excretion rate was higher after ingestion of the raw test meal than after ingestion of the cooked meal. Significance was reached in the 9- to 24-h period.

The excretion pattern of [ring-$^2$H$_4$]phenol and p-[ring-$^2$H$_4$]cresol was similar to the excretion pattern of the unlabeled components (Fig. 6). p-[ring-$^2$H$_4$]cresol appeared in urine somewhat later than [ring-$^2$H$_4$]phenol. Overall, the maximal excretion rate was reached in the 9- to 24-h period. The cumulative percentage of administered dose of l-[ring-$^3$H$_4$]tyrosine, recovered in urine as total [ring-$^3$H$_4$]phenols, was significantly higher after ingestion of the raw test meal compared with the cooked test meal (20.63 ± 5.59% vs. 1.60 ± 0.44%, $P < 0.005$) (Table 3).

$^{15}$N Retention

The percentage of administered dose of $^{15}$N, retained in the nitrogen pool of the body after 72 h, was significantly lower after ingestion of the raw test meal compared with the cooked test meal (49.63 ± 2.69% vs. 63.16 ± 1.36%, $P = 0.0002$) (Table 3).

Correlations

Significant correlations were found between several fecal, urinary, and breath variables (Table 5). There was a negative correlation between the recovery of $^{13}$C in breath and the recovery of either $^{15}$N in feces ($r = -0.94$).

Table 3. Major urinary and fecal variables in the two test situations

<table>
<thead>
<tr>
<th>Variable</th>
<th>Test Situation</th>
<th>Cooked</th>
<th>Raw</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feces</td>
<td>Wet weight, g/day</td>
<td>149.2 ± 22.3</td>
<td>152.0 ± 24.9</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>Dry weight, g/day</td>
<td>25.3 ± 2.7</td>
<td>27.1 ± 1.7</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>Dry matter, %</td>
<td>37.7 ± 5.1</td>
<td>41.2 ± 6.7</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>N excretion, g/day</td>
<td>1.89 ± 0.18</td>
<td>2.10 ± 0.29</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>N density, %dry matter</td>
<td>5.02 ± 0.47</td>
<td>5.09 ± 0.55</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>%Cumulative $^{15}$N (c)</td>
<td>4.16 ± 0.27</td>
<td>14.50 ± 1.70</td>
<td>0.0002</td>
</tr>
<tr>
<td></td>
<td>R (d)</td>
<td>67.7 ± 3.7</td>
<td>74.0 ± 4.8</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>Total phenols, mg/day</td>
<td>32.14 ± 3.50</td>
<td>47.10 ± 5.06</td>
<td>0.0040</td>
</tr>
<tr>
<td></td>
<td>N excretion, g/day</td>
<td>10.38 ± 0.67</td>
<td>10.68 ± 0.57</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>%Cumulative $\Delta^{2}$H (e)</td>
<td>1.60 ± 0.44</td>
<td>20.63 ± 5.59</td>
<td>0.00010</td>
</tr>
<tr>
<td></td>
<td>%Cumulative $^{15}$Nf (f)</td>
<td>32.68 ± 1.35</td>
<td>35.91 ± 2.12</td>
<td>0.12</td>
</tr>
<tr>
<td>Calculated values</td>
<td>%Malabsorbed (c + c)</td>
<td>5.73 ± 0.50</td>
<td>35.10 ± 6.78</td>
<td>0.0020</td>
</tr>
<tr>
<td></td>
<td>%Accumulation (c/c + e)</td>
<td>24.14 ± 6.07</td>
<td>50.62 ± 6.10</td>
<td>0.0030</td>
</tr>
<tr>
<td></td>
<td>%Incorporation (c/c + c)</td>
<td>75.86 ± 6.07</td>
<td>49.38 ± 6.10</td>
<td>0.0030</td>
</tr>
<tr>
<td></td>
<td>%Retained in N pool (100% − c − f)</td>
<td>63.16 ± 1.36</td>
<td>49.63 ± 2.69</td>
<td>0.00020</td>
</tr>
</tbody>
</table>

Values are means ± SE; $n = 10$. %Cumulative $^{15}$Nf = $\sum_{0h}^{72h}$% dose $^{15}$Nadm corrected (see text). R = $\sum_{0h}^{72h}$% dose $[^3]$HPEG 4000 (see text). %Cumulative $\Delta^{2}$H = $\sum_{0h}^{72h}$% dose $^2$Hadm corrected (see text). %Cumulative $^{15}$Nadm = $\sum_{0h}^{72h}$% dose $^{15}$Nadm (see text). %Incorporation assumes that 100% of $^{15}$N recovered in feces is incorporated into the bacterial mass. P values were obtained by paired t-test.

Table 4. Fecal $^{15}$N excretion in 10 healthy volunteers after ingestion of a cooked and raw test meal consisting of 25 g of $^{13}$C-, $^2$H-, and $^{15}$N-labeled egg protein

<table>
<thead>
<tr>
<th>Excretion per day, %dose/day</th>
<th>Cumulative excretion</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-24 h</td>
<td>24-48 h</td>
</tr>
<tr>
<td>Cooked</td>
<td>0.34 ± 0.27</td>
</tr>
<tr>
<td>Raw</td>
<td>1.81 ± 1.37</td>
</tr>
<tr>
<td>P</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Values are means ± SE; $P$ values were obtained by paired t-test. adm. Administered.
The efficacy of protein assimilation has been studied to date by several researchers either in ileostomy subjects (4, 8, 11, 22, 32, 34) or in healthy volunteers using intubation techniques (24). It was demonstrated that the amount of protein escaping digestion and absorption in the small intestine is affected by the type and amount of protein (8, 11, 16, 22, 34) as well as the presence of other constituents (e.g., resistant starch) (32) in the diet. Less is known about the process of protein fermentation in vivo in humans, which is largely due to the physiological inaccessibility of the colon.

The availability of protein labeled with stable isotopes allowed us to study protein (mal)absorption and fermentation in healthy volunteers by means of noninvasive tracer techniques. An inherent advantage of tracer techniques is that they do not disturb normal physiology. All volunteers were studied in two different randomly applied test situations: 1) after ingestion of a cooked egg protein meal labeled with L-[1-13C]leucine, [15N]amino acids, and L-[ring-2H4]tyrosine and 2) after ingestion of the same but raw meal. Both test situations were separated by a 1-wk washout period. This period was sufficiently long to return isotope enrichment to baseline (data not shown).

Protein (mal)absorption and fermentation were evaluated quantitatively through the analysis of metabolites excreted in breath, urine, or feces. Breath was analyzed for 13CO2, feces for 15N, and urine for [ring-2H4]phenol, p-[ring-2H4]cresol, and 15N.

The breath test results obtained in the present study were in accordance with those obtained in a recent study performed in ileostomy patients under similar test conditions (8). In the latter study, a highly significant negative correlation was demonstrated between the 13C recovery in breath and the recovery of exogenous protein in the ileal effluents. In the extrapolation of this finding to subjects with an intact gastrointestinal system, the low recovery of 13CO2 in breath after ingestion of the raw protein test meal suggests overt malabsorption.

It may be argued that in subjects with an intact gastrointestinal system the 13CO2 recovered in breath may be derived from the fermentation of malabsorbed L-[1-13C]leucine in the colon as well. However, because it was observed in the ileostomy study formerly mentioned (8) that 50% of the malabsorbed cooked and raw protein had emptied from the ileostomy by 5.33 and 5.29 h, respectively, it can be assumed that most of the 13CO2 appearing in breath within 6 h following the
ingestion of the labeled test meal is derived from the metabolism of protein assimilated in the small intestine.

The mean daily fecal wet weight, dry weight, and nitrogen content were consistent with previous investigations in humans (2, 7, 36, 37). None of these parameters was affected significantly by the nature of the test meal (Table 3).

The cumulative percentage of administered dose of $^{15}$N recovered in feces over 72 h after ingestion of the cooked egg protein meal amounted to $4.16 \pm 0.27\%$. This value is comparable with figures previously reported for yeast, egg, and soya protein (20, 40). The cumulative recovery of $^{15}$N in feces after ingestion of the raw meal was significantly higher ($14.50 \pm 1.70\%$). It has previously been demonstrated that at least 60% of the fecal nitrogen content is of bacterial origin (36). For practical purposes, however, it is assumed in the present study that all $^{15}$N recovered in feces is of bacterial origin (i.e., incorporated in the bacterial mass).

The cumulative percentage of administered dose of $^{2}$H recovered in urine over 72 h amounted to $1.60 \pm 0.44\%$ and $20.63 \pm 5.59\%$, respectively, after ingestion of the cooked and raw test meal. The percentage of administered dose of $^{2}$H recovered in urine represents the portion of consumed egg protein that is accumulated in the colonic lumen as free fermentation metabolites, subsequently absorbed into the portal blood and finally excreted in urine.

The excretion pattern of $^{2}$H$_4$-labeled total phenols after ingestion of the raw test meal coincided almost completely with the excretion pattern of the unlabeled fraction. This indicates that the observed increase of the unlabeled total phenols is related to malabsorption of the test meal. $[\text{ring-$^{2}$H}_4]$phenol appeared in urine slightly earlier than p-$[\text{ring-$^{2}$H}_4]$cresol. This is in accordance with previous studies suggesting that phenol and p-cresol are predominantly formed in the terminal ileum (and cecum) and left colon, respectively (3). The delayed appearance of p-cresol might also be explained by a slower production rate.

Assuming that the fate of both the $^{15}$N and $^{2}$H tracer is identical in the large intestine, the percentage of ingested protein that escaped digestion and absorption could be calculated approximately. It amounted to $5.73 \pm 0.50\%$ and $35.10 \pm 6.78\%$ after ingestion of the cooked and raw test meal, respectively (Fig. 8). Malabsorption might be overestimated in the present study.

### Table 5. Correlations between breath, fecal, and urinary variables

<table>
<thead>
<tr>
<th>Breath variable</th>
<th>Fecal Variables</th>
<th>Urinary Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>%Dose $^{13}$C 6 h</td>
<td>Total N, g/day</td>
<td>Total phenol, mg/day</td>
</tr>
<tr>
<td></td>
<td>Wet weight, g/day</td>
<td>%Cumulative $^{15}$N</td>
</tr>
<tr>
<td></td>
<td>%Cumulative $^{15}$Nf</td>
<td></td>
</tr>
<tr>
<td></td>
<td>%Cumulative $^{2}$H$_4$</td>
<td></td>
</tr>
<tr>
<td>Fecal variables</td>
<td>%Cumulative $^{15}$Nf</td>
<td></td>
</tr>
<tr>
<td>Wet weight, g/day</td>
<td>0.10</td>
<td>-0.049</td>
</tr>
<tr>
<td>%Cumulative $^{15}$Nf</td>
<td>-0.71†</td>
<td>0.19</td>
</tr>
<tr>
<td>%Cumulative $^{2}$H$_4$</td>
<td>-0.67†</td>
<td>-0.62†</td>
</tr>
<tr>
<td>Fecal variables</td>
<td>Total phenol, mg/day</td>
<td>%Cumulative $^{2}$H$_4$</td>
</tr>
<tr>
<td>%Cumulative $^{15}$Nf</td>
<td>-0.67†</td>
<td></td>
</tr>
<tr>
<td>%Cumulative $^{2}$H$_4$</td>
<td>0.11</td>
<td></td>
</tr>
</tbody>
</table>

n = 20 (10 subjects x 2 test situations). *P < 0.05; †P < 0.005.

Fig. 7. Correlations between parameters of protein assimilation (i.e., %cumulative $^{13}$C) and parameters of protein malabsorption (i.e., %cumulative $^{15}$N and %cumulative $^{2}$H$_4$). %cum $^{13}$C, cumulative percentage of administered dose of $^{13}$C recovered in breath over 6 h. %cum $^{15}$N, %cum $^{15}$Nf, %cum $^{2}$H$_4$, %cum $^{2}$H$_4$adm corrected (see text for complete explanation of abbreviations).

Fig. 8. Amount and fate of 25 g of egg protein escaping assimilation in the small intestine of humans.
due to tracer recycling. Tracer recycling occurs through desquamation of intestinal mucosa and secretion of digestive enzymes and urea in the small intestine and colon, respectively (20, 26). Little information is available on the magnitude of this bias, which, most probably, is due to methodological problems. Kayser et al. (20) quantified $^{15}\text{N}$ tracer recycling by measuring the appearance of $^{15}\text{N}$ in stools after an intravenous injection of 250 mg of $^{15}\text{N}$-enriched glycine (99 AP). The fractional fecal loss (i.e., tracer recycling) amounted to $1.43 \pm 0.64\%$ (means $\pm$ SD). Although it is reasonable that the magnitude of tracer recycling is not fixed but influenced by dietary factors, the latter value may be indicative.

Despite possible overestimation due to tracer recycling, the malabsorption percentages observed in the present are still somewhat lower than those we previously reported in healthy ileostomy patients in identical test conditions (8). This difference can be explained either by differences in the efficiency of protein assimilation between healthy volunteers and ileostomy patients or by salvage of nitrogen in the colon (18). The latter possibility is supported by human and animal data (17, 21).

Amounts of 24.14 $\pm$ 6.07% and 50.62 $\pm$ 6.10% of the malabsorbed cooked and raw egg protein, respectively, were calculated to accumulate as free end products of bacterial metabolism in the colonic lumen (Fig. 8). Assuming that the two test conditions only differed in the amount of protein made available to the colon, the present results support the hypothesis that luminal accumulation as free fermentation metabolites becomes the preferential fate of malabsorbed protein as more protein is made available to the colon.

Significant differences were observed between both test situations in the pattern of excretion rates of $^{15}\text{N}$ in urine. The $^{15}\text{N}$ excretion rate was significantly lower in the 0- to 6-h period and significantly higher in the 9- to 72-h period after ingestion of the raw test meal compared with the cooked test meal. Protein assimilation was suggested by the shape of the breath test curve to be completed after 6–9 h. Bacterial protein metabolism, reflected by an increase of the excretion of [ring-\(^{2}\text{H}\)]phenols in urine, on the other hand, became apparent from 9 h after ingestion of the test meal on. Therefore, $^{15}\text{N}$ appearing soon after ingestion of the test meal is accepted to be derived uniquely from the metabolism of assimilated protein, whereas $^{15}\text{N}$ appearing later on is accepted to be derived from bacterial metabolism of malassimilated protein as well. As could be predicted, metabolism of assimilated protein was more prominent after ingestion of the cooked test meal, whereas bacterial metabolism of malassimilated protein was more prominent after ingestion of the raw protein meal. Notwithstanding these kinetic differences, the cumulative percentage of administered dose of $^{15}\text{N}$ excreted in urine over 72 h was similar in both test situations.

The cumulative percentage of administered dose of $^{15}\text{N}$, retained in the nitrogen pool of the body, was significantly lower after ingestion of the raw protein meal compared with the cooked protein meal. Nevertheless, the difference between both test situations (13.50 $\pm$ 2.20%) was less pronounced than was expected from the difference in the percentage of malabsorption (29.34 $\pm$ 6.45%) (Table 4). This observation might equally be explained by salvage of nitrogen in the colon.

Highly significant negative correlations were found between parameters of protein assimilation (i.e., cumulative percentage of administered dose of $^{13}\text{C}$, recovered in breath over 6 h) and parameters of protein malabsorption (i.e., the amount of $^{15}\text{N}$ and [ring-\(^{2}\text{H}\)]phenols, recovered in feces and urine, respectively). This finding supports the validity of the techniques used. The lack of a significant correlation between the fecal nitrogen output and fecal $^{15}\text{N}$ recovery indicates that the fecal nitrogen output may not be regarded as a sensitive parameter of the efficiency of dietary protein assimilation in the small intestine.

In conclusion, using noninvasive stable isotope techniques, we were able to evaluate protein (mal)absorption and fermentation in healthy volunteers in a noninvasive and quantitative way. We definitively confirmed malabsorption of even easily digestible protein. Our further support the hypothesis that an increased availability of protein in the colon causes the preferential fate of malabsorbed protein to shift toward luminal accumulation as free protein fermentation metabolites. This finding may be important from a gastrointestinal point of view, since several of these metabolites (ammonia, thiols, phenols) are thought to play a role in the etiopathogenesis of, e.g., ulcerative colitis and colonic cancer (3, 5, 10, 23, 27, 28, 30, 39).

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Address for reprint requests and other correspondence: Y. Ghoos, Universitair Ziekenhuis Gasthuisberg, Laboratorium Digestie.Absorptie E 462, Herestraat 49, B-3000 Leuven, Belgium (E-mail: Yvo.Ghoos@uz.kuleuven.ac.be).

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