A valid, accurate, office based non-radioactive test for gastric emptying of solids

J S Lee, M Camilleri, A R Zinsmeister, D D Burton, L J Kost, P D Klein

Abstract

Background—Current breath tests for measurement of gastric emptying of solids are expensive, possibly inaccurate, and require cumbersome calculations.

Aims—We wished to validate a simplified solid gastric emptying test using a [13C]Spirulina platensis breath test for accurate results relative to scintigraphy.

Subjects—Thirty healthy volunteers.

Methods—We measured gastric empting of egg containing [13C]S platensis and 99mTc sulphur colloid by breath [13C] and scintigraphy over six hours. A generalised linear regression model was used to predict t1/2 and tLAG by scintigraphy from breath [13C] data. The model was cross validated and normative data calculated for a prepacked [13C]meal.

Results—Regression models using all breath data over six hours, for the first three hours, and for samples at 75, 90, and 180 minutes (“reduced model”) predicted t1/2 and tLAG values similar to scintigraphy (t1/2= 43 (SD 12) min; tLAG 100 (20) min). Standard deviations of differences in t1/2 and tLAG between scintigraphy and the “reduced model” were both 10 minutes. Gastric t1/2 for the prepacked [13C]meal was 91 (15) min (10–90% range: 74–118).

Conclusion—The [13C]S platensis breath test and a simple formula using breath [13C] at baseline, 90, and 180 minutes measured gastric emptying t1/2 for solids with results that were comparable with scintigraphy.

Keywords: stable isotope; breath test; gastric emptying

Gastric emptying of solids is used to screen for gastric motor disorders. Two parameters that are clinically useful are t1/2 and the proportion emptied at four hours; these reflect overall emptying functions. The time for the first 10% to empty (or lag time) is a marker for the ability of the stomach to triturate solid food to a particle size that can be emptied (<2 mm3). These measurements (tLAG, tLAG) are best estimated by scintigraphy and the state of the art analysis uses a power exponential or a nonlinear model.

Stable isotope breath tests were recently introduced to measure gastric emptying of solids because of their potential advantages, which include performance of the test at the bedside or in the community; remote laboratory automated analysis; application at sites where gamma camera facilities are not available; and avoidance of radiation, facilitating research studies in children and pregnant women.

The lack of validity for interindividual comparisons is a significant pitfall; inaccuracies of the test may result partly from the nonlinear models used to fit the cumulative breath [13C]CO2 recoveries. In the breath test, the total gastric residual is unknown and is estimated by a formula where time is infinite and [13C]CO2 excretion is assumed to have reached a steady state. Estimates of gastric half-emptying time (t1/2) and lag phase duration (tLAG) using nonlinear models are determined by the shape of the curve and are independent of endogenous CO2 production. The results, however, are strongly associated with the estimated parameter “m” or estimated gastric residual. In contrast, scintigraphy can be used to follow complete emptying of the stomach, an unequivocal end point. In our previous studies using the conventional nonlinear model, we determined that accurate determination of the parameter “m” in healthy subjects (that is a steady [13CO2] excretion state) required at least six hours of breath collection. We anticipated that patients with impaired gastric emptying may require an even longer sampling time, suggesting the breath test may become impractical.

From a review of simultaneous scintigraphic and [13C]CO2 cumulative excretion curves performed in nearly 70 healthy volunteers in our laboratory, we noted that the “tail” of the cumulative excretion curve often did not reach steady state conditions; moreover, this portion of the curve corresponded to a time when all of the 99mTc isotope had emptied from the stomach. Thus optimizing the curve fit might represent a futile exercise unrelated to the process of emptying.

In the present study we aimed to develop a new mathematical model for breath data analysis that was independent of the parameter “m” and would offer accuracy with shorter (three hours or less) sampling times. This new mathematical model was developed while assessing the accuracy of a breath test using a [13C] substrate consisting predominantly of the protein [13C]Spirulina platensis (described below). Subsequently, the model was further validated using the leave-one-out method. Finally, we performed the [13C]S platensis breath test in a simulated office based practice using a standardised prepacked [13C]biscuit commercial meal and compared the results with those of the [13C]S platensis egg meal.

Abbreviations used in this paper: t1/2, half-emptying time; tLAG, lag time.

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Materials and methods

Subjects
Thirty healthy volunteers, aged 18–53 years (mean 34 (SE 1.6); 15 males, 15 females; median body mass index 23 kg/m² (range 18.7–39.1)), were recruited by public advertisement. None had previously undergone abdominal surgery other than appendicectomy. None was receiving medications. Females of childbearing potential had a negative pregnancy test within 48 hours of beginning the study. A clinical interview and physical examination were performed and none of the subjects was receiving medications that could influence gastrointestinal motility or autonomic function. Written informed consent was obtained before participation in the study which was approved by the Institutional Review Board and the Radiation Control Committee of the Mayo Clinic.

S platensis is an edible blue-green alga used as a protein source in many parts of the world and sold as a food supplement in health food stores.² The protein contains 50–60% protein, 30% starch, and 10% lipid.⁴ The S platensis used in this study was grown as a pure monoculture in a closed hydroponics chamber in a medium containing inorganic salts and purged with pure ¹³CO₂. The resultant cells were uniformly labelled with ¹³C; the natural level of ¹³C in the environment (about 1%) was increased to 99% in the substrate used. When metabolised, the proteins, carbohydrates, and lipids of the S platensis give rise to respiratory CO₂ that is enriched in ¹³C. Because the contents of the algal cells are not freely diffusible, incorporation of labelled S platensis into a solid phase meal occurs easily and represents the digestive state of the solid food matrix within which it is contained.

Scintigraphic data
A region of interest was drawn around the stomach on the anterior and posterior images for each time frame. To correct for tissue attenuation, the counts in each region were corrected using the same mathematical method.

Data analysis

Scintigraphic data
13CO₂ enrichment determined by isotope ratio mass spectrometry was expressed as the delta per mil difference between the ¹³CO₂/¹²CO₂ ratio of the sample and standard. ¹³CO₂ in the breath samples was calculated as atom percent excess (percentage ¹³CO₂ in total CO₂ above background ¹³CO₂ concentration in nature) as in previous studies.¹⁸–²⁰ The results of the breath test were presented as a percentage of ¹³CO₂ recovery per hour and as a cumulative value over six hours. ¹³CO₂ production was assumed to be 300 mmol per square metre of body surface area per hour as published by Ghos et al.²¹ Body surface area was calculated using a validated weight-height formula.

To calculate the quantity of ¹³C appearing in breath per unit time, delta over baseline (DOB) was used: ¹³C (µM/min)=DOB×0.0112372×CO₂ production, where 0.0112372 is the isotopic abundance of the limestone standard, Pee Dee Belemnite, and CO₂
production was corrected for individual basal metabolic rates according to age (<3, 3–10, 10–18, 18–30, 30–60, >60 years) and gender as determined by Schofield.

Figure 2  Comparison of gastric lag phase duration (tLAG) (A) and half-emptying times (t1/2) for scintigraphy and breath tests using the generalised linear regression model (GLM), shown as median values (bars), interquartile ranges (boxes), range from 10th to 90th percentiles (bar caps), and practical data over the 10th to 90th percentiles (dots) for scintigraphy and breath tests. Note the excellent agreement between scintigraphy and generalised linear models.

STATISTICAL ANALYSIS

Generalised linear regression model to predict scintigraphic estimates of gastric half-emptying time and lag phase using breath test values

A generalised linear multiple regression analysis was used to develop a model for predicting the scintigraphic gastric emptying estimates for t1/2 and tLAG using 13C values from breath samples obtained over the first three hours after the meal. In this generalised linear model approach, t1/2 and tLAG values were assumed to follow a gamma distribution (positively skewed distribution) to account for a common situation in clinical practice where data from patients with gastroparesis, or dumping syndrome, often lead to a skewed distribution of gastric emptying t1/2 and tLAG values. The link function used to relate the linear predictor (weighted combination of 13C values at the multiple time points) to scintigraphically observed tLAG (or t1/2) values was the inverse (reciprocal) function. A preliminary analysis of the (reciprocally) transformed t1/2 and tLAG values using a simple stepwise multiple regression model (maximum r2 method) provided candidate subsets of breath sample times to consider as “reduced models” (that is, fewer time points) in the generalised regression (gamma) model analysis.

As it is possible that evaluation of models to estimate tLAG and t1/2 may give an overly optimistic assessment when based on the same data, an internal cross validation analysis was used to assess the results of the “reduced models”. Thus a “leave-one-out” approach was used to obtain the breath sample prediction for each subject. In this analysis, each individual subject is left out of the calculations to estimate the regression parameters of the linear predictor for the gamma regression model; then the predicted value for the subject omitted from the model (or left out) is computed using the regression model results based on the remaining subjects included (or left in) the model. This is done repeatedly with each subject in turn being left out and used as a (quasi) external validation observation.

Comparisons of the adequacy of fit of the models between the full six hour data compared with the three hour data or the “reduced models” were based on the difference in log likelihood values for each model. Similarly, the adequacy of fit for the three hour data and the “reduced models” were compared.

In addition, estimates of t1/2 and tLAG by the full and “reduced models” were compared using a (non-parametric) Wilcoxon signed rank test of the differences resulting from different estimation methods (for example a paired comparison of the absolute values of (scintigraphic t1/2 minus breath sample estimated t1/2)). The correlation between scintigraphically determined values (observed values) and predicted values (for the various estimation methods) were computed, and the distribution of simple residuals (observed-predicted) summarised.

The distributions of t1/2 and tLAG estimates from the breath test using either the egg meal
or the biscuit meal in 27 healthy subjects were compared.

Results

COMPARISON OF GASTRIC EMPTYING INDICES BETWEEN SCINTIGRAPHY AND THE BREATH TEST USING A GENERALISED LINEAR REGRESSION MODEL PREDICTING SCINTIGRAPHIC RESULTS

Gastric emptying by scintigraphy yielded mean values of 43 (SD 12) minutes for \( t_{LAG} \) and 100 (20) minutes for \( t_{1/2} \). The generalised linear regression models predicting scintigraphic \( t_{LAG} \) based on the entire six hour and the first three hour breath test data for \(^{13}\)C breath excretion did not differ significantly \((r=0.79 \text{ and } 0.72, \text{ respectively})\). Twice the difference in log likelihood values (which is approximated by a chi-square distribution) was 5.0 on 6 degrees of freedom (p=NS). The standard deviation of the difference between the observed \( t_{LAG} \) and the predicted values computed using the three hour breath test data was eight minutes (range −22 to 19) (fig 1A). The generalised linear models predicting scintigraphic \( t_{LAG} \) based on the entire six hour and the first three hour breath test data for \(^{13}\)C breath excretion did not differ significantly \((r=0.91 \text{ and } 0.86, \text{ respectively})\); difference in log likelihood, 7.5 on 6 degrees of freedom; NS). The standard deviation of the differences between \( t_{LAG} \) from scintigraphy and the predicted value computed using the “reduced model” was 10 minutes (range −27 to 29).

A summary of the mathematical models using data from three breath test samples (75, 90, 180 minutes) is: \( t_{LAG} = 1/LP_{LAG} \) where \( LP_{LAG} = 0.0250 + 0.0063^{C_{180}} - 0.0032^{C_{120}} \) and for \( t_{1/2} \): \( t_{1/2} = 1/LP_{1/2} \) where \( LP_{1/2} = 0.0097 + 0.0021^{C_{180}} - 0.0012^{C_{120}} \).

In these formulas, \( t_{LAG} \) and \( t_{1/2} \) are predicted \( t_{LAG} \) and \( t_{1/2} \) using breath test concentrations in \( \mu\text{mol/min} \) at the specific times 75, 90, and 180 minutes; \( LP_{LAG} \) and \( LP_{1/2} \) are the linear predictors (that is, weighted sums of breath test concentrations); and \(^{13}\)C is the excreted quantity of \(^{13}\)C \((\mu\text{mol/min}) \) for time \( t=75,90, \text{ or } 180 \text{ minutes} \).

GASTRIC EMPTYING PARAMETERS IN HEALTHY SUBJECTS USING BREATH TEST AND SCINTIGRAPHY

Figure 2 summarises gastric emptying indices for 30 healthy volunteers from scintigraphy and various breath test results (a generalised linear regression model using the three hour data and a generalised linear regression “reduced model” using only two time points). The predicted \( t_{LAG} \) and \( t_{1/2} \) values from the generalised linear regression (“reduced models”) were similar to the scintigraphic values (fig 2).

CROSS VALIDATION ANALYSIS OF THE GENERALISED LINEAR REGRESSION REDUCED MODEL

Figure 3 summarises the cross validation assessment of the “reduced model” for estimating the scintigraphic gastric emptying parameters \( t_{LAG} \) and \( t_{1/2} \). The standard deviation of the differences for \( t_{LAG} \) was 11 minutes (range −23 to 23) and for \( t_{1/2} \) 13 minutes (range −29 to 31). Figure 4 indicates a slightly broader distribution of residuals compared with those in fig 3C and D. However, the cross validated predicted values showed little change in the correlation coefficients.
Table 1  Normal values of gastric emptying indices of the \textsuperscript{13}C\textit{S} platensis breath test in healthy volunteers (minutes)

<table>
<thead>
<tr>
<th>Test meal (N)</th>
<th>Variable</th>
<th>Median</th>
<th>Q1–Q3</th>
<th>10–90th</th>
<th>Min-Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Egg meal (30)</td>
<td>( t_{LAG} )</td>
<td>43</td>
<td>36–47</td>
<td>33–53</td>
<td>27–59</td>
</tr>
<tr>
<td></td>
<td>( t_{1/2} )</td>
<td>104</td>
<td>86–111</td>
<td>77–120</td>
<td>65–130</td>
</tr>
<tr>
<td>Biscuit meal (27)</td>
<td>( t_{LAG} )</td>
<td>38</td>
<td>33–42</td>
<td>28–49</td>
<td>26–51</td>
</tr>
<tr>
<td></td>
<td>( t_{1/2} )</td>
<td>88</td>
<td>80–102</td>
<td>73–118</td>
<td>67–120</td>
</tr>
</tbody>
</table>

Q1–Q3, interquartile range; 10–90th, 10th to 90th percentile values; \( t_{LAG} \), lag time; \( t_{1/2} \), half-emptying time.

STANDARD MEAL STUDY USING THE \textsuperscript{13}C\textit{S} PLATENISS BISCUIT

Twenty seven of the 30 original participants were recruited for a repeat gastric emptying study using \textsuperscript{13}C\textit{S} platensis biscuit, a prepacked standard meal. In fig 4, the distributions of \( t_{LAG} \) and \( t_{1/2} \) estimates using the generalised linear regression model based on three breath \textsuperscript{13}CO\textsubscript{2} excretion data points are shown for the \textsuperscript{13}C\textit{S} platensis egg meal and the \textsuperscript{13}C\textit{S} platensis biscuit meal. There were small differences in \( t_{1/2} \) estimates within individuals (median three minutes, range −18 to 49) for the two meals and these differences are consistent with the day to day variation in normal gastric emptying (median 12–15%) previously reported. These differences are also summarised in table 1.

Discussion

Our laboratory has further pursued the goal of developing a simple, non-radioactive office based, or field based, breath test using stable isotopes to measure gastric emptying of solids. Our data suggest that the methods proposed are ready for clinical application and for use in epidemiological studies. We showed that sufficiently accurate estimates of \( t_{1/2} \) and \( t_{LAG} \) using the \textsuperscript{13}C\textit{S} platensis breath test could be obtained using the new method compared with scintigraphic methods. Mathematical analysis of breath test data appears to be important. In a subsequent application of the new approach, we showed that it can also be applied to measurement of gastric emptying of solids with \textsuperscript{13}C\textit{C}octanoic acid as the substrate.

Our approach was to develop an analytical model which could overcome the essential difference between scintigraphy and breath tests, that is the unknown total gastric residual when a breath test is used. Following our observation that the early portion of the cumulative \textsuperscript{13}CO\textsubscript{2} breath curves was generally linear (and reciprocal to the scintigraphic emptying curve), we sought the time points during the three hour period of breath sampling which best reflected the scintigraphic estimates of gastric emptying in healthy subjects. Using this method we determined that three breath samples during the first three hours provided essentially equivalent information compared with estimates from all breath samples obtained during the three hour test. We have shown, using a generalised linear model approach, that the three hour data were essentially equivalent to the estimates from the six hour breath test, and that both gave good estimates of \( t_{LAG} \) and \( t_{1/2} \) determined by scintigraphy. These time points (particularly at 90 and 180 minutes) most closely reflected the gastric half-emptying time. Interestingly, these time points are earlier than the time when one would anticipate errors from the redistribution of \textsuperscript{13}C from the body’s bicarbonate pool which occurs typically more than three hours after a meal.

Using the generalised linear regression “reduced model”, breath samples were needed at only four times: baseline, 75, 90, and 180 minutes after the meal, with three data points each for \( t_{LAG} \) (baseline, 75, and 180 minutes) and \( t_{1/2} \) (baseline, 90, and 180 minutes). Moreover, the calculations were simplified relative to the nonlinear approach; predicted \( t_{LAG} \) and \( t_{1/2} \) can be estimated using a pocket calculator. This simplified method can be applied in epidemiological or multicentre studies because of its safety, simplicity, accuracy, and low cost relative to scintigraphy.

As our model was developed based on data from 30 healthy volunteers, it is possible that our approach reflects only physiological gastric emptying. However, because the model incorporated a non-Gaussian data distribution, we anticipate it would be similarly accurate in disease states, particularly in delayed gastric emptying. We have validated the use of the model in diabetic patients using a \textsuperscript{13}C\textit{C}octanoic acid meal as the source of \textsuperscript{13}C\textsubscript{2}. The relatively accurate of the test using \textsuperscript{13}C spirulina substrates in disease states requires further study.

A final departure from previous studies in this analysis was the use of the actual quantity of \textsuperscript{13}C appearing in breath per minute. This was used to further simplify the calculation, obviating the need to collect all data points for the cumulative excretion plot. A delta over baseline value or a percentage of \textsuperscript{13}CO\textsubscript{2} recovery per hour can also be used, but we found that actual \textsuperscript{13}C values reflected the most accurate overall results.

In summary, new calculations render the stable isotope \textsuperscript{13}C\textit{S} platensis breath test comparable with scintigraphy for estimating gastric emptying in healthy volunteers. The normal values for a standardised preprepared meal containing \textsuperscript{13}C were estimated. These approaches need to be applied in disease states and may ultimately enable the development of an office or field based non-radioactive test to measure gastric emptying of solids in humans.

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Potential conflict of interest: Dr P D Klein is an employee of Meretek Diagnostics, Inc. Two US patents have been awarded to Meretek Diagnostics, Inc. (Nos 5,707,602 and 5,785,949) covering the use of \textsuperscript{13}C spirulina (\textit{S} platensis) in solid and liquid phase gastric emptying measurements.

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