Combined Carbon-13-Glycine/Carbon-14-Octanoic Acid Breath Test to Monitor Gastric Emptying Rates of Liquids and Solids

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The aim of the present study was to develop a dual-carbon-labeled breath test for simultaneously measuring gastric emptying rates of liquids and solids with significantly less radiation burden to the patient than the radioscintigraphic technique. **Methods:** A test meal was used in which the liquid phase was labeled with two markers, i.e., 3.7 MBq of ^{111}In-DTPA and 100 mg of ^{13}C-glycine; the solid phase also was dually labeled with 110 MBq of ^{99m}Tc-albumin colloid and 74 kBq of ^{14}C-octanoic acid. Simultaneous radioscintigraphic and breath-test measurements were performed in 27 subjects, 10 normal controls and 17 patients with dyspeptic symptoms. Mathematic analysis of the excretion rate of labeled CO_2 allowed the definition of four parameters, i.e., the gastric emptying coefficient, the gastric half-emptying time, the peak excretion time and the lag phase. **Results:** There was a good to excellent correlation between the gastric emptying coefficient and the scintigraphic half-emptying time ($r = 0.74$ for liquids and $r = 0.88$ for solids), between the half-emptying time determined by breath test and the scintigraphic half-emptying time ($r = 0.91$ for liquids and $r = 0.92$ for solids), between the peak excretion time and the scintigraphic half-emptying time ($r = 0.91$ for liquids and $r = 0.96$ for solids) and between the lag phase of solid emptying determined by both techniques ($r = 0.89$). **Conclusion:** The dual carbon-labeled breath test is a valid, minimally invasive technique to measure the gastric emptying rate of both liquids and solids.

Key Words: gastric emptying; breath test; radioscintigraphy; carbon-14-octanoic acid; carbon-13-glycine; indium-111-DTPA; technetium-99m-albumin

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The solid, liquid and oil phase of a meal are handled differently by the stomach and are emptied at different rates. Accurate measurement of gastric emptying in normal and pathologic conditions requires that these be measured separately (*1–3*). Radioscintigraphic techniques with two different radionuclides allow the measurement of liquid and solid gastric emptying simultaneously (*4*). However, the technique of multiple radionuclide markers and labeling requires a well-equipped laboratory, and the examination procedure imposes a substantial amount of radiation on the patient (*5*). To minimize the radiation hazard for the patient and to make measurement of gastric emptying more accessible to standard hospital practice, the authors set out to develop breath tests for measuring gastric emptying of solids and liquids. The radiopharmaceutical ^{14}C-octanoic acid was selected as a marker for the solid phase. The results of these studies have been published recently (*6*). In addition, ^{13}C-glycine was selected as a marker of the liquid phase because it is easily solubilized in water and rapidly absorbed and converted into $^{13}CO_2$ after it enters the small intestine. A ^{13}C liquid marker was used, not only to eliminate radiation hazard, but also to allow simultaneous measurement of both the solid and liquid phase of the meal. The ^{14}C-octanoic acid and the ^{13}C-glycine breath test were evaluated by performing simultaneous radioscintigraphic and breath-test measurements of a quadruple-labeled test meal in 27 subjects.

METHODS

Subjects

Ten healthy volunteers (three women and seven men, mean age 25 yr, range 19–27 yr) and 17 patients (10 women and seven men, mean age 43 yr, range 19–65 yr) with dyspeptic symptoms were included in the study. The subjects had no history of previous gastrointestinal surgery and were not taking any medication affecting gastric motility. The gastric emptying rate of the liquid and solid phase of the test meal was measured simultaneously by radioscintigraphy and by $^{13}CO_2$/$^{14}CO_2$ breath sample analysis.

Test Meal

All subjects performed the test at 8:00 a.m. after an overnight fast of at least 12 hr. The test meal consisted of a beaten egg, two slices of white bread and 5 g of margarine. The egg was dosed with 74 kBq of [1-^{14}C]-octanoic acid, sodium salt (DuPont, NEN Research, Boston, MA) and 110 MBq of ^{99m}Tc-albumin colloid (Ultra Technicow, Malinckrodt Medical, Petten, The Netherlands). After homogenization, the yolk was baked separately from the egg white to ensure firm labeling. The egg white was baked around the yolk afterward. The meal was ingested within 10 min, immediately followed by 150 ml of water, dosed with 100 mg of [1-^{13}C]-glycine

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(99% enrichment; Isotec, Miamisburg, OH) and 3.7 MBq of ^{111}In-DTPA (Ultra Technicow). The total caloric value of the test meal was 250 kcal.

Measuring Techniques

To measure the retention of the liquid and solid phase in the stomach, each subject was seated between the two heads of a dual-headed gamma camera, equipped with parallel-hole low-energy collimators and interfaced to a computer. Scanning scintigraphic information was obtained every 10 min up to 1 hr and every 15 min for another 1 hr. The liquid and solid still present in the stomach at each scanning period were expressed as retention, i.e., as the percentage of the activity of ^{111}In initially and ^{99m}Tc, respectively, present. The activity present immediately after ingestion of the meal was taken as 100%.

Breath sampling for $^{13}CO_2$ and $^{14}CO_2$ measurements followed the same time schedule as the scintigraphic technique but lasted another 2 hr of sampling at 15-min intervals. For $^{13}CO_2$ measurements, breath was collected in a 3-l aluminum-coated balloon (Tesseraux, Bürstadt, Germany). The ^{13}C breath content was determined by isotope ratio mass spectrometry (Finnigan MAT 250, Bremen, Germany) or by on-line gas chromatographic purification-isotope ratio mass spectrometry (ABCA, Europa Scientific, Crewe, UK). The $^{14}CO_2$ in breath was collected by blowing through a pipette into vials containing 2 mmole of hyamine hydroxide until decoloration of the thymolphtoleine indicator, corresponding to the capture of 2 mmole of CO_2. The $^{14}CO_2$ was measured by beta scintillation counting. For both carbon labels, CO_2 production was assumed to be 300 mmole/m^2 of body surface per hour. The body surface area was calculated by the weight-height formula of Haycock et al. (*7*). The results of the $^{13}CO_2$ and $^{14}CO_2$ breath test were expressed as the percentage $^{13}CO_2$ and $^{14}CO_2$, respectively, excreted per hour by calculating procedures described elsewhere (*8*).

Data Analysis

The data obtained by radioscintigraphic measurement were fitted by the modified power exponential formula of Siegel et al. (*9*). Half-emptying time ($t_{1/2s}$) was calculated according to the following formula by SAS computer program (PROC NLIN) (*10*):

$$y = 1 - (1 - e^{-kt})^{\beta}, \qquad \text{Eq. 1}$$

where y is the fractional dose of ^{111}In or ^{99m}Tc still retained in the stomach compared with the initial dose; t time in hours; and k and β are constants. The half-emptying time is given by following equation:

$$t_{1/2s} = (-1/k) \cdot \ln(1 - 2^{(-1/\beta)}). \qquad \text{Eq. 2}$$

The lag phase of the solid phase was calculated as the first 5% of activity (^{99m}Tc) evacuated out of the stomach and expressed as:

$$tlag_s = \left(\frac{1}{k}\right) \cdot \ln(1 - 0.05^{(+1/\beta)}). \qquad \text{Eq. 3}$$

The data obtained by breath test were fitted by two mathematic formulas using the least-square procedure. The best fit was retained. The first formula is given by

$$\text{(I) } y = at^b e^{-ct}, \qquad \text{Eq. 4}$$

where y is the percentage of $^{13}CO_2$ or $^{14}CO_2$ excretion, respectively, in breath per hour; t is time in hours; and a, b and c are constants. The second formula is expressed as

$$\text{(II) } y = mk\beta e^{-kt}(1 - e^{-kt})^{\beta - 1}, \qquad \text{Eq. 5}$$

where y is the percentage of ^{13}C/^{14}C excretion in breath per hour; t is time; m, k and β are constants; and m is the total cumulative ^{13}C/^{14}C recovery when time is infinite. This formula is the first derivative of the modified power exponential formula of Siegel et al. (*9*) with a correction factor m. Nonlinear-regression analysis was performed using the least-squares method by NONLIN program (SAS, Raleigh, NC) (*10*) or a computer program written in Excel 4.0 for a 80386T computer (Mys G, personal communication, 1992).

Three parameters of gastric emptying of liquids were calculated. First is the gastric emptying coefficient (GEC), corresponding to ln(a) of the first formula and a global indicator for the gastric emptying rate. The second is the $t_{1/2b}$, the breath-test-determined gastric half-emptying time, calculated by numeric integration in the first formula or by the following equation using the second formula:

$$t_{1/2b} = (-1/k) \cdot \ln(1 - 2^{(-1/\beta)}). \qquad \text{Eq. 6}$$

The value of the best-fitted curve was retained. The third is the peak $^{13}CO_2$ ($^{14}CO_2$) excretion time, i.e., the time of maximal $^{13}CO_2$ ($^{14}CO_2$) excretion of the fitted curve, calculated by following equation derived from the first formula:

$$t_{max} = b/c, \qquad \text{Eq. 7}$$

or by the following equation using the second formula:

$$t_{max} = \ln(\beta)/k. \qquad \text{Eq. 8}$$

This point corresponds to the time of maximal gastric emptying rate. The value of the best-fitted curve was retained.

The lag phase of the solid phase was calculated as the first 5% of $^{14}CO_2$ of the total amount excreted using numeric integration in the first formula or following equation for the second formula:

$$tlag_b = (1/k) \cdot \ln(1 - 0.05^{(+1/\beta)}). \qquad \text{Eq. 9}$$

Again, the value of the best-fitted curve was retained.

Statistical Evaluation of Results

The relationship between the scintigraphically measured half-emptying time ($t_{1/2s}$) and the lag phase ($tlag_s$) and the data obtained by breath-sample analysis [(GEC), half-emptying time ($t_{1/2b}$), peak excretion time (t_{max}) and lag phase ($tlag_b$)] were evaluated by correlation and linear-regression analysis (PROC CORR and PROC REG, SAS) (*10*). The breath-test-determined half-emptying times and solid lag phases were compared with the scintigraphically determined half-emptying times and solid lag phases using paired-comparisons t-tests (PROC MEANS, SAS) (*10*).

RESULTS

Liquid Phase

Figure 1 shows the gastric emptying rate of liquids measured by the two techniques in three typical examples. Figure 1A represents the $^{13}CO_2$ excretion curve of a subject with rapid gastric emptying rate ($t_{1/2s}$ = 18 min); Figure 1B shows the breath-test data of a subject with normal gastric emptying rate of liquids ($t_{1/2s}$ = 47 min); and Figure 1C shows a delayed gastric emptying pattern ($t_{1/2s}$ = 148 min). The solid lines represent the curve fitting; the circles represent the breath-test data. These figures clearly show that increasing radioscintigraphic half-emptying times corresponded to characteristic changes in the $^{13}CO_2$ excretion curves. The inclination of the ascending part and the declination of the descending part of the curve decreased, and the peak of curve 1C was both diminished and delayed.

In Figure 2, the scintigraphically measured half-emptying time is compared with the gastric emptying parameters determined by breath test. In Figure 2A, the relationship between the scintigraphically and breath-test-determined half-emptying time ($t_{1/2b}$ versus $t_{1/2s}$) is shown. The correlation coefficient between the two parameters is 0.91 ($p < 0.0001$). Linear-regression analysis results in the following equation $t_{1/2b} = 70 + 0.97 \times t_{1/2s}$. This regression line has a slope of nearly 1 with an intercept of the regression line at time zero of 70 min. Using this regression model, the breath-test-determined half-emptying times can be recalculated to the scintigraphically determined half-emptying times. Paired-comparison t-tests showed no significant difference between these "corrected" breath-test-determined half-emptying times and the scintigraphically determined half-emptying times ($p = 0.8355$). Figure 2B illustrates the relationship between the scintigraphically determined gastric half-emptying time ($t_{1/2s}$) and the peak excretion time (t_{max}). The linear-regression line between these two parameters is given by $t_{max} = 45 + 0.95 \times t_{1/2s}$ with a correlation coefficient of 0.91 ($p < 0.0001$). Figure 2C shows the relationship between the scintigraphically determined half-emptying time and the GEC; the regression line is expressed by $GEC = 3.50 - 0.013 \times t_{1/2s}$ with a correlation coefficient $r = 0.74$ ($p < 0.0001$). Figure 3 displays the corrected breath-test-determined half-emptying times, using the regression model.

Table 1 gives the normal values of the 10 healthy control subjects examined in this study of the scintigraphically determined half-emptying time and the three breath-test-determined parameters.

Solid Phase

Figure 4 illustrates the gastric emptying rate of solids in three typical examples. Figure 4A shows the $^{14}CO_2$ excretion curve of a subject with a rapid emptying rate ($t_{1/2s} = 39$ min); Figure 4B represents a normal gastric emptying pattern ($t_{1/2s} = 69$ min); Figure 4C shows a delayed gastric emptying rate ($t_{1/2s} = 131$ min). The circles represent the measured data, with the solid lines, the fitted curve. Comparison of the different $^{14}CO_2$ excretion curves for gastric emptying of solids indicates that the ascending and descending slopes of the curves diminish and that the peak excretion of $^{14}CO_2$ occurs later and is slower with increasing scintigraphically determined half-emptying times.

The relationship between the scintigraphically determined gastric half-emptying time ($t_{1/2s}$) and the breath-test-determined half-emptying time ($t_{1/2b}$) is given in Figure 5A; the correlation coefficient is 0.92 ($p < 0.0001$). The linear-regression line between these two parameters is given by the equation $t_{1/2b} = 74 + 1.04 \times t_{1/2s}$. This line parallels the bisectrice, which allows easy recalculation of the scinti-

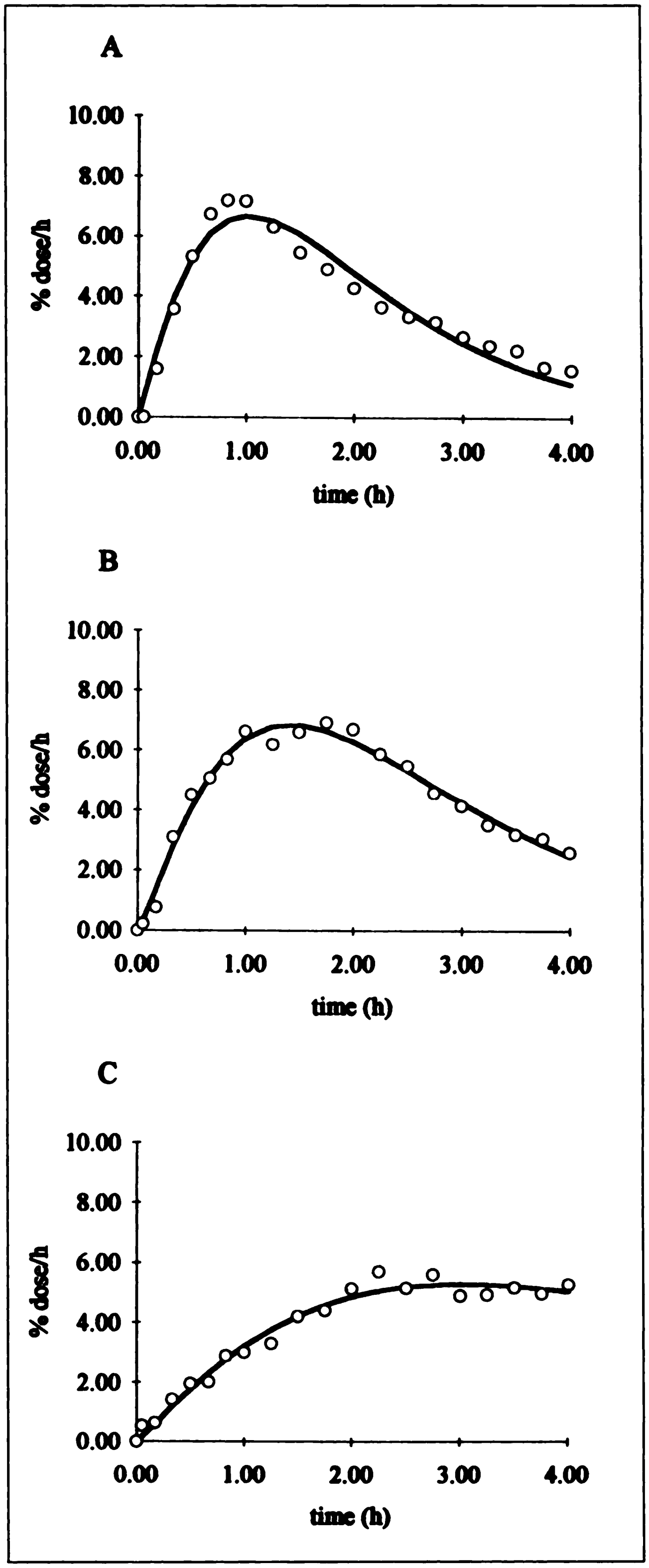

FIGURE 1. Results of the ^{13}C-glycine breath test in three typical cases. (A) A rapid gastric emptying pattern ($t_{1/2s} = 18$ min). (B) A normal gastric emptying curve ($t_{1/2s} = 47$ min). (C) A delayed gastric emptying pattern ($t_{1/2s} = 148$ min).

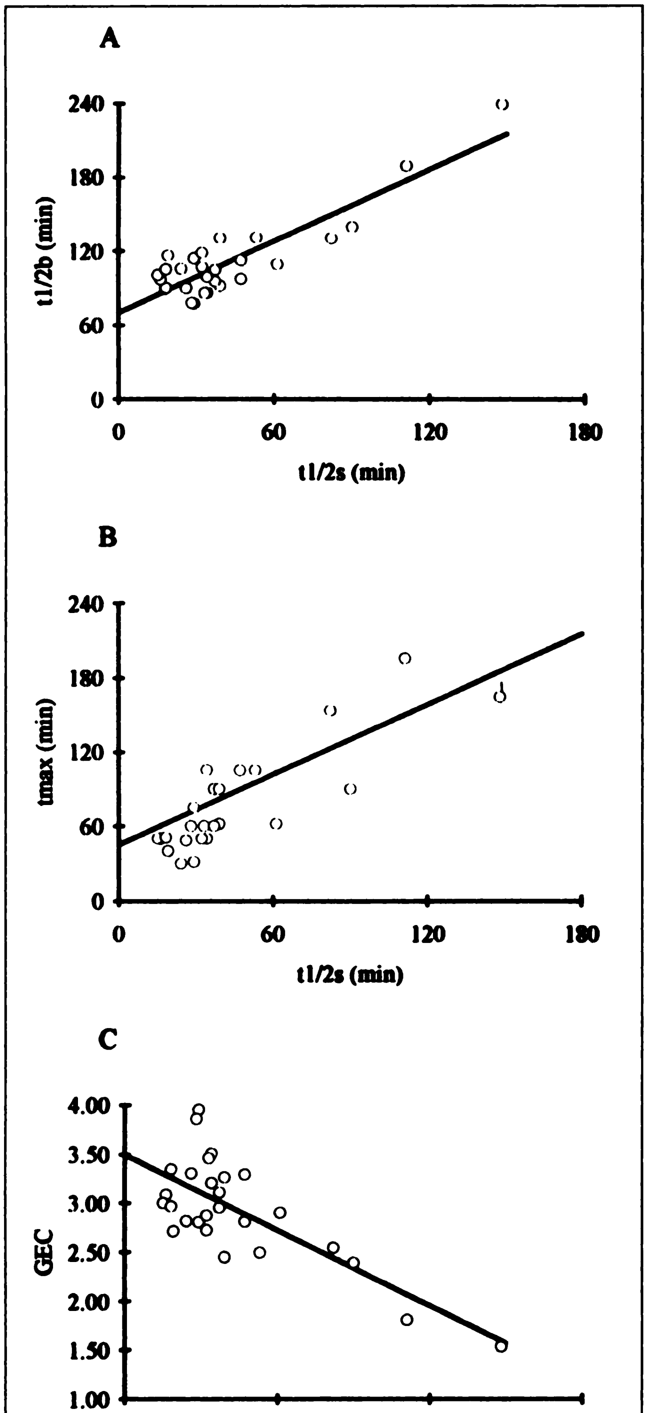

FIGURE 2. Comparison of the radioscintigraphically determined half-emptying time with the breath-test-determined parameters for the liquid phase: the half-emptying time (A), the peak excretion time (B) and the GEC (C). Also the regression lines (solid lines) between the scintigraphically determined parameters and the breath-test parameters are given.

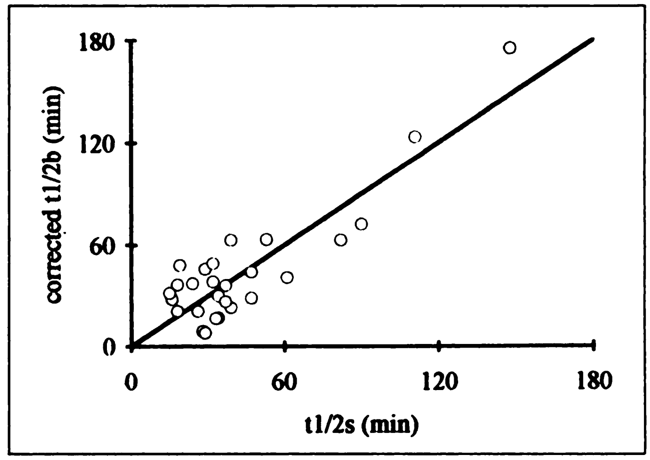

FIGURE 3. Comparison between the scintigraphically determined half-emptying time and the corrected breath-test-determined half-emptying time, based on the regression model. The regression line (solid line) between both parameters is also given.

graphically half-emptying times from the breath-test-determined half-emptying times using this regression model. Figures 5B and 5C represent the relationship between the scintigraphically determined half-emptying time ($t_{1/2s}$) and the breath-test-determined peak excretion time (t_{max}) and GEC, respectively. The regression lines correspond to the following equations: $t_{max} = 41 + 0.83 \times t_{1/2s}$ ($r = 0.96$, $p < 0.0001$) and $GEC = 3.98 - 0.01 \times t_{1/2s}$ ($r = 0.87$, $p < 0.0001$). Figure 5D illustrates the relationship between the lag phase of solid emptying determined by both techniques. The regression line corresponds to $tlag_b = 26 + 0.82 \times tlag_s$; the correlation coefficient between both is 0.89 ($p < 0.0001$). Figure 6 represents the corrected values of the breath-test-determined half-emptying time ($t_{1/2bcorr}$); they were not statistically different from the scintigraphically determined half-emptying times ($p = 0.9991$) with a regression line expressed by $t_{1/2bcorr} = 1.00 \times t_{1/2s}$.

In Table 2, the primary descriptive statistics are given for the different scintigraphically and breath-test-determined gastric emptying parameters of the 10 normal healthy control subjects used in this study.

TABLE 1
Mean, s.d. and s.e.m. of the Scintigraphically Determined Half-Emptying Time and the Three Breath-Test-Determined Parameters for the Liquid Phase for the 10 Normal Control Subjects

	$t_{1/2s}$ (min)	GEC	$t_{1/2b}$ (min)	Corrected $t_{1/2b}$ (min)	t_{max} (min)
Mean	38.4	3.03	105.0	36.1	72.0
s.d.	18.2	0.47	19.6	20.2	38.4
s.e.m.	5.8	0.15	6.21	6.4	12.0

$t_{1/2s}$ = scintigraphically determined gastric half-emptying time; $t_{1/2b}$ = breath-test-determined gastric half-emptying time; t_{max} = peak excretion time; GEC = gastric emptying coefficient.

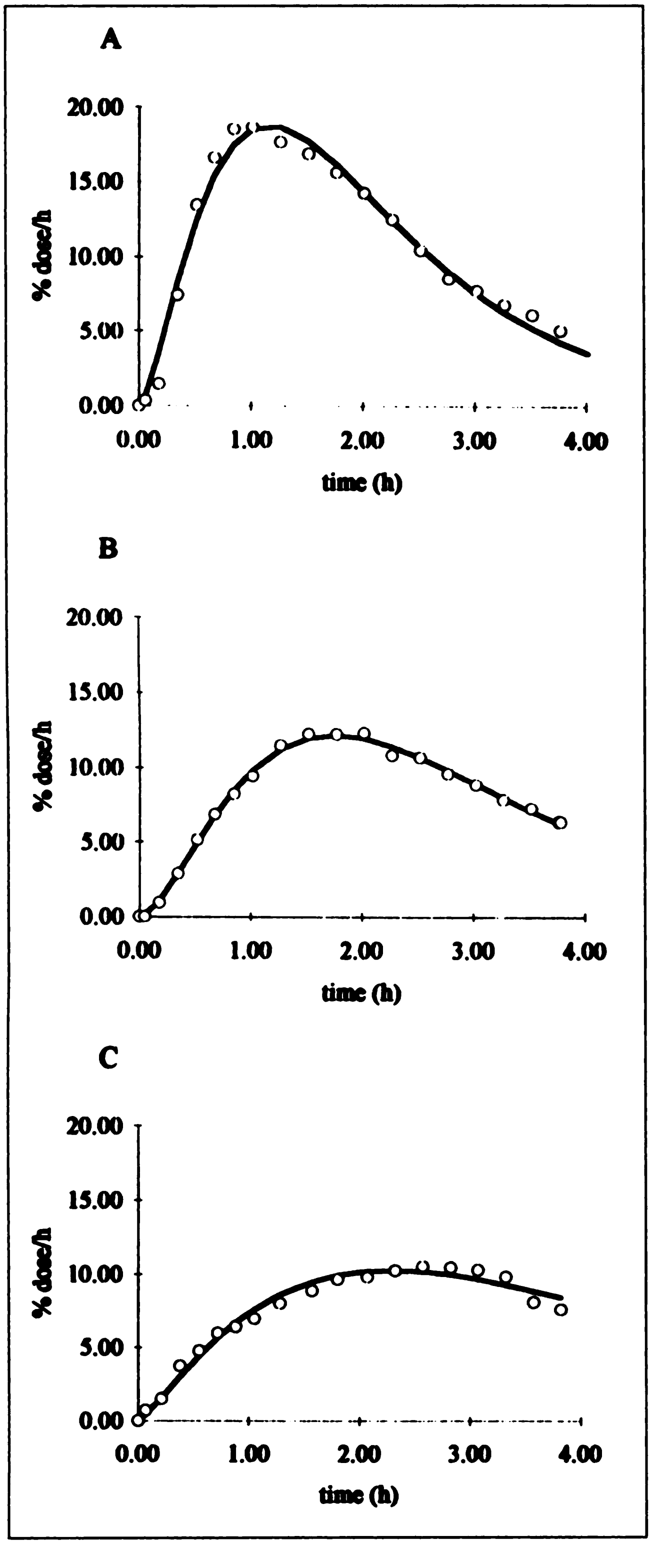

FIGURE 4. Results of the ^{14}C-octanoic breath test in three typical cases. (A) A rapid gastric emptying pattern ($t_{1/2s}$ = 39 min). (B) A normal gastric emptying curve ($t_{1/2s}$ = 69 min). (C) A delayed gastric emptying pattern ($t_{1/2s}$ = 131 min).

DISCUSSION

These results indicate that the breath tests described in this article allow the measurement of gastric emptying of solids and liquids with an accuracy similar to that of radioscintigraphy. As in radioscintigraphic techniques, emptying of the solid phase of a meal can be measured simultaneously with liquid emptying. To demonstrate this, a quadruple-labeled test meal was used with ^{13}C-glycine and ^{111}In-DTPA labeling the liquid phase and ^{14}C-octanoic acid and ^{99m}Tc-albumin colloid marking the solid phase. This type of test meal is considered a standard test meal for scintigraphic gastric-emptying studies. By simultaneous measurement of the retention of scintigraphic markers in the stomach and the excretion of labeled CO_2 in breath, the two techniques can be accurately compared.

The breath-test markers used to measure gastric emptying were ^{14}C-octanoic acid for the solid phase and ^{13}C-glycine for the liquid phase of the meal. The ^{14}C-octanoic acid breath test was validated in another study by simultaneous radioscintigraphic measurement of ^{99m}Tc-albumin colloid and the analysis of $^{14}CO_2$ excretion in breath after the intake of solid test meal, labeled with both ^{99m}Tc-albumin colloid and ^{14}C-octanoic acid. Octanoic acid was a good marker for the solid test meal used, with a rapid duodenal absorption and hepatic oxidation; the breath test showed a good correlation with the scintigraphic technique for all determined gastric-emptying parameters (*6*). Glycine was selected as marker of the liquid phase because it is easily soluble in water (*11*). It is postulated that glycine is not absorbed in the stomach; the site of absorption of glycine and other neutral amino acids is located in the proximal intestine, using mainly active transport mechanisms (*12*). After transport across the intestinal wall, glycine is partly oxidized to CO_2 by different pathways (*13,14*).

Although the carbon-labeled glycine and octanoic acid breath tests are indirect methods to measure the gastric emptying rate of liquids and solids, respectively, mathematic analysis of the labeled CO_2 excretion curves allows a description of the liquid and solid emptying rate in much the same way as the radioscintigraphic technique.

The breath-test-determined half-emptying time correlates well with the scintigraphically determined half-emptying time. The regression line between these two parameters has a slope of nearly 1, with the point of intersection with the y-axis lying at ±70 min. This delay between the scintigraphically and breath-test-determined half-emptying time, calculated by regression analysis, is almost identical for both glycine and octanoic acid. This observation indicates that differences in absorption, metabolism and excretion of the two markers are minimal. Recalculating the breath-test-determined half-emptying times, corrected on the basis of the regression models, results in values similar to those obtained by radioscintigraphy.

The peak excretion time, defined as the time of maximal labeled CO_2 recovery of the fitted curve, is related to the

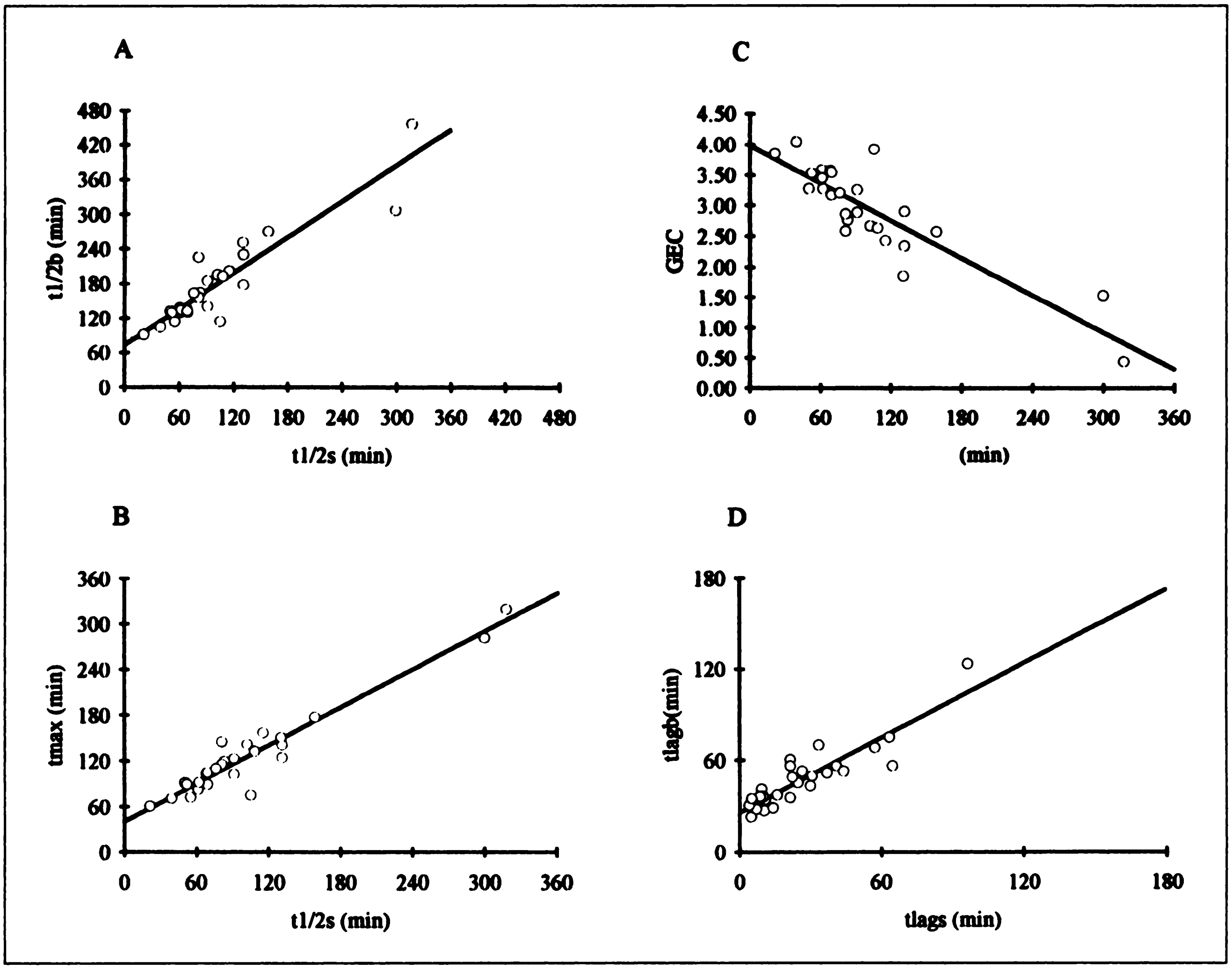

FIGURE 5. Comparison of the radioscintigraphically determined half-emptying time with the breath-test-determined parameters for the solid phase: the half-emptying time (A), the peak excretion time (B) and the GEC (C). (D) The relationship between the lag phases determined by both techniques. Also the regression lines (solid lines) between the scintigraphically determined parameters and the breath-test parameters are given.

labeled CO_2 recovery of the fitted curve, is related to the maximal gastric emptying rate. Although this parameter has a different physiologic meaning than the half-emptying time, the peak excretion time correlates well with the scintigraphically determined half-emptying time, accepting an average delay between both parameters of 45 min.

The good correlation of both the breath-test-determined gastric half-emptying time and the peak excretion time with the radioscintigraphic half-emptying time is probably caused by the fact that these two breath-test parameters are, by the nature of their mathematic definition, independent of the endogenous CO_2 production and the amount of ^{13}C-glycine that is converted to CO_2. These parameters are only dependent on the shape of the CO_2 excretion curve. Studies with ^{14}C-glycine show that the amount of glycine metabolized to $^{14}CO_2$ may be reduced in some pathologic conditions, but the shape of the $^{14}CO_2$ excretion curve remains unaltered (*15*). Moreover, despite the different

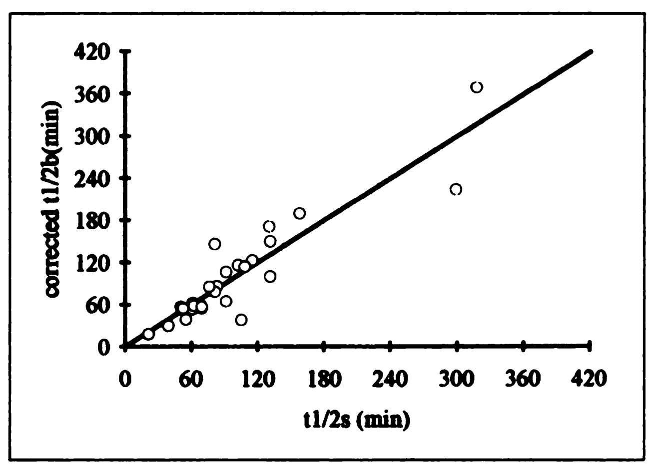

FIGURE 6. Comparison between the scintigraphically determined half-emptying time and the corrected breath-test-determined half-emptying time, based on the regression model. The regression line is represented as a solid line.

TABLE 2
Mean, s.d. and s.e.m. of the Scintigraphically Determined Half-Emptying Time and Lag Phase and the Four Breath-Test-Determined Parameters for the Solid Phase for the 10 Normal Control Subjects

	$t_{1/2a}$ (min)	$tlag_a$ (min)	GEC	$t_{1/2b}$ (min)	Corrected $t_{1/2b}$ (min)	t_{max} (min)	$tlag_b$ (min)
Mean	61.7	16.90	3.29	133.51	68.22	93.00	37.96
s.d.	23.21	11.29	0.39	28.26	27.17	21.08	10.81
s.e.m.	7.34	3.57	0.12	8.94	8.59	6.67	3.42

$t_{1/2a}$ = scintigraphically determined gastric half-emptying time; $t_{1/2b}$ = breath-test-determined gastric half-emptying time; t_{max} = peak excretion time; GEC = gastric emptying coefficient.

tabolized after absorption (as shown by the peak excretion [percent of the dose per hour] in the CO_2 excretion curves), regression analysis between the scintigraphically determined half-emptying time and the breath-test-determined half-emptying time and peak excretion time resulted in nearly the same regression lines for both markers. This finding indicates that absorption, metabolism and excretion are not the rate-limiting steps in these processes. However, further validation is needed in the future in regard to metabolic diseases.

The GEC, although a reliable index for the global assessment of the gastric emptying rate of liquids and solids, does not correlate well with the radioscintigraphic half-emptying time. This may be partly caused by the fact that this parameter is dependent on the amount of labeled CO_2 excreted and partly also by the fact that, in very rapid gastric emptying patterns, this parameter can be underestimated by fitting deficiencies (Fig. 1C). This, however, is not a major disadvantage because visual control of the labeled CO_2 excretion curve demonstrates that the fitted curve underestimates the process in this subject.

The breath-test-determined solid lag phase, which is also independent of the total amount of labeled CO_2 excreted, correlates well with the scintigraphic solid lag phase and therefore gives additional information on the early pattern of gastric emptying of the solid meal.

Because the pattern of gastric emptying of liquids and solids can be adequately described by dual-labeled CO_2 breath sample analysis, using biexponential models, the combined ^{13}C-glycine and ^{14}C-octanoic acid breath testing can be a valid alternative for the radioscintigraphic method to monitor gastric emptying. The ^{13}C-glycine breath test compares favorably with other tests of liquid gastric emptying, e.g., aspiration technique (*16*), radioscintigraphy (*5*), paracetamol absorption test (*17*), the echographic method (*18*) and the recent MRI technique (*19*). Combined with the ^{14}C-octanoic acid breath test, this dual-label breath test may be a good alternative for radioscintigraphy for the simultaneous measurement of liquid and solid emptying.

Although lacking information about intragastric distribution of the different phases of the test meal, breath-test measurements of gastric emptying offer several advantages over radioscintigraphic techniques. The combined breath test is minimally invasive and exposes the patient to significantly less ionizing radiation than radioscintigraphy. The whole-body radiation with the breath-test method is less than 0.015 mGy (for 74 kBq of ^{14}C-octanoic acid) compared with 0.78 mGy for the combined scintigraphic technique (0.54 mGy for 110 MBq of ^{99m}Tc-albumin colloid and 0.24 mGy for 3.7 MBq of ^{111}In-DTPA) (*20–27*). This allows repeated emptying studies to be done in a short period (e.g., detection of transient disorders, evaluation of the influence of therapeutic actions and evaluation of the day-to-day variability in the individual patient). In addition, breath tests are easy to perform, even for elderly or disabled patients, and can be carried out at the bedside, with several tests being done simultaneously in different patients. Breath tests do not immobilize costly equipment or dedicate an investigator's time for a single patient during a considerable period. Breath samples can be analyzed after completion of the sampling at a convenient time. Moreover, latest developments in isotope ratio mass spectrometry also make $^{13}CO_2$ measurements readily accessible to clinical laboratories; in addition, breath tests can be performed outside the hospital, because the labeled CO_2 samples can be sent to an analytic center.

In conclusion, the combined ^{13}C-glycine/^{14}C-octanoic acid breath test is a safe and valid test for measuring the gastric emptying rate of liquids and solids simultaneously, thereby reducing radiation exposure to the patient.

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