Validity of the doubly labeled water method for estimating CO₂ production in mice under different nutritional conditions

Stefano Guidotti,1,2 Harro A. J. Meijer,1 and Gertjan van Dijk1,2
1Center for Isotope Research, Energy and Sustainability Research Institute Groningen, University of Groningen, Groningen, The Netherlands; 2Center for Behavior and Neurosciences, Unit Neuroendocrinology, University of Groningen, Groningen, The Netherlands

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The doubly labeled water (DLW) technique is used to assess metabolic rate (MR) in free-living conditions. We investigated whether differences in the nutritional and body adiposity status affect validity of the assessment of CO₂ production (rCO₂) by the DLW technique. To serve this purpose, we compared calculated rCO₂ by the DLW method to actual CO₂ production concomitantly measured in an indirect calorimetry setup over a 3-day period in mice fed a low-fat (LF) diet or an obesogenic high-fat/high-sucrose (HF) diet. To uncover a potential effect of body composition on DLW accuracy, the HF-fed group was further subdivided in a diet-induced obesity-prone (DIO) and diet-induced obesity-resistant (DR) group. Furthermore, we assessed the influence of different sampling protocols, duration, and methodology of calculation. An excellent match was found between rCO₂ assessed by the two methods in the LF-fed mice (least discrepancy −0.5 ± 1.1%). In contrast, there was a consistent overestimation of rCO₂ by the DLW technique in the HF-fed animals compared with actual CO₂ production independent from body mass gain (least discrepancy DR +15.9 ± 2.2%, DIO +18.5 ± 3.2%). The least discrepancies were found when two-pool model equations and the intercept method were used to calculate the body water pool. Furthermore, the HF group presented different equilibration kinetics of ²H and ¹⁸O and a lower dilution space ratio between the two. We recommend particular caution when using the DLW method for MR assessment in HF-fed animals and potentially humans because of the overestimation of rCO₂.

body composition; diet-induced obesity; doubly labeled water; metabolic rate; validation

The current epidemic of obesity has spurred the need for understanding how energy balance and body weight are regulated and how derangements in these can develop. The doubly labeled water (DLW) technique has served this demand because it is an isotopic tracer method ideally suited for measuring metabolic rate (MR) and body composition in free-living conditions. As such, the DLW method has been used in laboratory as well as field studies to assess MR in a variety of species, including humans, migratory birds, and rodents (19, 27, 39).

DLW is a water mixture in which the natural abundant forms of hydrogen (¹H) and oxygen (¹⁸O) have been partially or totally replaced with the low abundant stable isotopic forms (²H and ¹⁸O, respectively). The method is based on the straightforward principle that hydrogen leaves the body primarily via water turnover, whereas oxygen leaves the body both via water turnover and via CO₂ production. The difference between the two elimination rates allows the estimation of the rate of CO₂ production (rCO₂) over time. By introducing a known mass of the DLW mixture in the body by injection or drinking, enrichments of body fluids by ²H and ¹⁸O are determined at an initial and final time point from which elimination rates can be determined. rCO₂ can be converted to MR by using an estimated or measured respiratory quotient (RQ) on the basis of the equation of Weir (38). This allows assessment of MR and body composition in conditions where confinement in an indirect calorimetry setup (i.e., where the actual rates of rCO₂ and O₂ consumption, rO₂, are determined) is impossible to perform, since it would conflict with the study design. Examples of these are assessment of MR in animals living in a social context (3), in flight energy expenditure during bird migration (39), in lactation energetics (Guidotti S, Jónás I, Schubert K, Garland T Jr, Meijer H, Scheurink A, and van Dijk G, unpublished observations), or during sleep deprivation (1, 2).

Despite the fact that the principle of DLW technique for calculation of MR is rather straightforward, it is based on several assumptions, as reported originally by Lifson and colleagues (20, 21), that may not always be met in experimental settings. Violation of these assumptions can have a negative impact on the validity of the assessment of rCO₂ and hence, MR (24, 31). One of the assumptions, particularly relevant in light of the use of the DLW technique for studying derangements in energy balance and obesity, is that hydrogen and oxygen do not compartmentalize beyond the water and CO₂ pool. However, hydrogen and oxygen probably violate this assumption since they could be incorporated into nonaqueous molecules via ionic exchange or anabolic metabolism, resulting in larger pool sizes and isotopic fractional washout rates. In fact, ²H incorporation into C-H bonds has been used in biomedical sciences to measure in vivo lipogenesis (36) or synthesis of macromolecules such as DNA (12).

To our knowledge, studies in mammals that compared rCO₂ assessed by indirect calorimetry to the level obtained by the DLW technique generally find overestimation by the latter (20, 23), which might be due to nutritional and/or energy balance parameters. Therefore, the main aim of this study was to investigate whether differences in the nutritional status and energy balance affect the validity of rCO₂ assessed by the DLW technique. To serve this purpose, we compared rCO₂ calculated by the DLW method with actual CO₂ production concomitantly measured using a calibrated CO₂ sensor in an indirect calorimetry setup over a 3-day period in mice fed a
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low-fat (LF) diet and an obesogenic high-fat/high-sucrose (HF) diet. To uncover a potential effect of body composition on DLW validity, the HF-fed group was further subdivided in a diet-induced obesity-prone (DIO) and diet-induced obesity-resistant (DR) group. Furthermore, we assessed the influence of different sampling protocols, duration, and method of calculation.

MATERIALS AND METHODS

Animals and housing. Thirty-two male outbred HSD:icr mice of 14 wk were initially used for this study. The mice were housed individually on a 12:12-h light-dark cycle (lights on 9 AM, lights off 9 PM) under temperature-controlled conditions (21 ± 1°C), with food and water ad libitum, in plexiglas cages (Macrolon Type II; UNO Roestvaststaal, Zevenaar, The Netherlands) with Envirorod wood shavings and a gnawing stick. After initial inclusion, eight of the mice were maintained on regular control (LF) laboratory chow (energy content: 15.9 KJ/g; 13% fat, 63% starch, and 24% protein, RMH-B 2181; HopeFarms, Woerden, The Netherlands), whereas the other 24 were switched to a 45% HF diet (energy content: 19.7 KJ/g; 45% fat, 18% starch, 13% sucrose, and 24% protein) 6 wk prior to the experiment. On the basis of body mass gain over the course of HF feeding, the mice were assigned to a DR or DIO group.

Experimental design. Under nonrestrictive conditions, LF- and HF-fed mice received an intraperitoneal injection of DLW (~0.15 g) weighing to the nearest 0.0001 g of enriched water consisting of 33.3% 2H and 66.6% 18O). Exactly 1, 2, and 3 h after dosing of the DLW mixture, blood was sampled from the mice by tail snip and flame-sealed into glass capillaries until determination of isotopic enrichment. Directly after sampling of the last initial sample, mice were transferred to indirect calorimetry cages with housing conditions similar to their home cage for 3 consecutive days. To reduce stress of novelty, wood shaving from their home cage was transferred as well. Exactly 24, 48, and 72 h after the third initial sample, indirect calorimetry was interrupted shortly for ~10 min. After the 72-h blood sample, HF-fed mice were euthanized for carcass analysis. These and all other experimental procedures were approved and guided by the local Animal Experimentation Committee of the University of Groningen.

Indirect calorimetry. The open-circuit indirect calorimeter system allowed determination of $rO_2$ (l/h) and $rCO_2$ (l/h) (37). In brief, $O_2$ and $CO_2$ concentrations of dried inlet and outlet air from each chamber were measured with paramagnetic $O_2$ analyzer (Servomex Xentra 4100, Crowborough, UK) and $CO_2$ by an infrared gas analyzer (Servomex 1440). The system recorded the differential in $O_2$ and $CO_2$ prior to each measurement. Flow rate corrections followed (distilled and undistilled).

Samples were measured in duplicates, unless a flaw was detected in the flame-sealing step. Maximum allowed duplicate differences were 5 and 2% of the value for $\delta^2$H values and 0.8 and 1.5% of the value for $\delta^{18}$O values (9). If the differences exceeded the above-mentioned levels, we examined the data critically and omitted the aberrant value, performing further calculations on a single replicate, and/or analyzed a third sample if available. More detailed information on how the analytical error propagating into $rCO_2$ was estimated is described elsewhere (9).

Isotope dilution spaces. Estimation of the body water pools for $^2$H (N2) and $^{18}$O dilution space (N0), using the plateau method, was performed according to the following equation:

$$N (mol) = \text{mol}_{\text{inj}} \left( \frac{E_{\text{ini}} - E_{\text{bkg}}}{E_{\text{bkg}} - E_{\text{ini}}} \right)$$

where N represents the dilution space or body water pool for $^2$H or $^{18}$O expressed in moles. $E_{\text{inj}}$ and $E_{\text{bkg}}$ are the enrichments at equilibrium and at background in the body, respectively. $E_{\text{ini}}$ is the enrichment of the injected water. $E$ is expressed in parts per million.

Estimation of the body water pools for $^2$H (N2) and $^{18}$O (N0) by the intercept method was performed by extrapolating the $E_{\text{ini}}$ back to the time of injection according to the following equation, with modifications (18):

$$E_{\text{ini}} = (E_{\text{ini}} - E_{\text{bkg}}) e^{k (t_{\text{ini}} - t_{\text{inj}})} + E_{\text{bkg}}$$

where $E_{\text{ini}} - E_{\text{inj}}$ is now the initial value to be used for the body water pools calculation, $t_{\text{ini}} - t_{\text{inj}}$ is the time between injection and the initial sampling (in h), and $k$ is the $^2$H or $^{18}$O turnover rate in h$^{-1}$.

Isootope turnover rates were calculated as follows:

$$k (mol/h) = \frac{\log_{10} (E_{\text{ini}} - E_{\text{bkg}}) - \log_{10} (E_{\text{ini}} - E_{\text{bkg}}^2)}{t}$$

where $E_{\text{ini}}$ represents the enrichment level at final sample and $t$ the time (in h) between final and initial sample. The initial body water pool TBW, was calculated by the isotope dilution method. TBW, as percentage of initial body mass was applied to the final body mass to estimate the final pool sizes.

For the multisample methodology the k values were calculated from the curves fitted along the values of samples collected during the 3-day measurement by using the 2-h time point as initial. Enrichment values above background were log transformed and curve-fitted; k values were derived from the slope of the regression line (least-squares fit).
Calculation of rCO₂. Several equations, presented in Supplemental Table S1 (supplemental data for this article can be found on the AJP-Endocrinology and Metabolism website), were employed for the calculation of rCO₂. N used in the equation was an average between initial and final body water pool. The first equation, applied in 1966 by Lifson and McClintock (21), used only the 18O dilution space (“one-pool model”) and considered only equilibrium fractionation factors at 24°C (see Supplemental Table S1, Eq. 1). Speakman further updated this equation by using a combination of in vivo kinetics and equilibrium fractionation factors at 37°C and assuming that they contribute in a ratio of 3:1 to the fractionated losses (see Supplemental Table S1, Eq. 2) (31). In two-pool model equations, both observed isotope pool sizes, NO and NO, are used in the estimation of rCO₂. The first equation used individual isotope spaces and the fractionation factors in Supplemental Table S1, Eq. 2 (see Supplemental Table S1, Eq. 3) (4). In 1986 and then in 1988, Schoeller and colleagues (27–29) updated the latter equation by using individual dilution space with fixed average pool size for oxygen and hydrogen pools relative to the body water pool (i.e., N₀ 1.01 and N₂ 1.04 times greater than actual dilution space and with a dilution space ratio of 1:03). The fractionation factors were estimated by equilibrium processes at 37°C, with fractionated water loss being equivalent to 2.3 times rCO₂ (see Supplemental Table S1, Eq. 4).

Racette et al. (26) further updated Schoeller’s equation in 1994 proposing that the population pool ratio was 1.034 (Supplemental Table S1, Eq. 8). Speakman et al. (32) also proposed a two-pool equation in 1993, but using a group dilution ratio, and they adopted the same fractionation factors as the ones used in Supplemental Table S1, Eq. 4. The equation was later update by Speakman (31) in 1997, using still a group dilution ratio but with the fractionation factors used in Supplemental Table S1, Eq. 2 (see Supplemental Table S1, Eq. 6) (31).

Finally, in 1980, Nagy (24) proposed an equation that does not use turnover rates (i.e., K₂ and K₀) but does use the log ratios of the initial and final isotope concentrations and directly incorporates initial and final pool sizes (N) as well as initial and final body mass of the animal under study (Supplemental Table S1, Eq. 7).

Apart from Supplemental Table S1, Eqs. 1 and 7, all equations are in fact only minor variations of each other. Yet, especially the choices for the level of fractionated water loss have a significant influence on the result. However, quantifying this fractionation experimentally is cumbersome (11, 14).

**Statistical analysis.** The data are expressed as means ± SE. Analysis was performed in Statistica (Statsoft). Multiple hour (initials) and day (finals) differences were tested with repeated-measures ANOVA (RM-ANOVA), with time as within factor and group as between factor. To test differences between groups, a general linear model ANOVA was used, followed by Tukey’s honestly significant difference post hoc testing.

**RESULTS**

**Body mass.** After being on the HF diet for 6 wk, eight of the mice that had the lowest weight gain were assigned to the DR group (n = 8; Δmass −0.05 ± 0.50 g), whereas another eight with the highest weight gain were assigned to the DIO group (n = 8; Δmass 6.12 ± 0.60 g). Using body masses on the day just before indirect calorimetry was started (day 0; Fig. 1, top left), ANOVA revealed group effects [F(2,21) = 13.69, P < 0.001], and post hoc analysis showed that mice in the HF-DIO group weighed significantly more than those in the HF-DR and LF groups. No differences were found between the HF-DR group and the LF group. In retrospect, the HF-DIO mice also weighed more than the HF-DR mice at the start of HF feeding [F(1,14) = 16.61, P < 0.01]. Percent body fat (see Fig. 1, top right) determined by isotopic dilution (see below) was affected by group [F(2,21) = 12.63, P < 0.001], and post hoc analysis showed that the HF-DIO mice had more fat relative to the LF mice (150 ± 8%) and HF-DR mice (113 ± 7%). No significant differences in percent body fat were found between HF-DR mice and LF mice (17 ± 16%).

Over the course of metabolic assessment by DLW/indirect calorimetry, HF-DIO mice reduced body mass slightly, whereas other groups remained stable [F(4,42) = 8.59, P < 0.001], rO₂ [F(4,42) = 4.45, P < 0.01], and RQ differences in percent body fat were found between HF-DR mice and LF mice (17 ± 16%).

**Indirect calorimetry.** During the placement of mice in the indirect calorimetry cages, the actual rCO₂, rO₂, and RQ were calculated by the isotope dilution method using the 2-hour initial plateau method (top right) in high-fat/high-sucrose (HF)-fed diet-induced obesity-prone (DIO; ▲ or black bar) and diet-induced obesity-resistant mice (DR; ■ or gray bar) and in LF-fed (● or open bar) mice. Isotopic equilibration and elimination curves in these groups for 2H and 18O are shown at bottom left and bottom right, respectively. Data are expressed as means ± SE. Tukey post hoc #LF vs. HF-DR or HF-DIO; #HF-DIO vs. HF-DR; #HF-DIO vs. HF-DR.
Table 1. Indirect calorimetry measurements during the 3-day validation study

<table>
<thead>
<tr>
<th></th>
<th>LF</th>
<th>HF-DR</th>
<th>HF-DIO</th>
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<tbody>
<tr>
<td><strong>rCO₂, ml/h</strong></td>
<td><strong>Day 1</strong></td>
<td><strong>Day 2</strong></td>
<td><strong>Day 3</strong></td>
</tr>
<tr>
<td></td>
<td>112.6 ± 3.8</td>
<td>116.0 ± 3.1</td>
<td>118.9 ± 2.9</td>
</tr>
<tr>
<td><strong>rO₂, ml/h</strong></td>
<td><strong>Day 1</strong></td>
<td><strong>Day 2</strong></td>
<td><strong>Day 3</strong></td>
</tr>
<tr>
<td></td>
<td>112.9 ± 4.9</td>
<td>116.6 ± 4.4</td>
<td>117.3 ± 3.5</td>
</tr>
<tr>
<td><strong>RQ, CO₂/O₂</strong></td>
<td><strong>Day 1</strong></td>
<td><strong>Day 2</strong></td>
<td><strong>Day 3</strong></td>
</tr>
<tr>
<td></td>
<td>1.00 ± 0.01</td>
<td>0.92 ± 0.01</td>
<td>0.92 ± 0.01</td>
</tr>
<tr>
<td><strong>MR, kJ/day</strong></td>
<td><strong>Day 1</strong></td>
<td><strong>Day 2</strong></td>
<td><strong>Day 3</strong></td>
</tr>
<tr>
<td></td>
<td>56.9 ± 2.3</td>
<td>58.8 ± 2.0</td>
<td>59.4 ± 1.7</td>
</tr>
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</table>

Data are expressed as means ± SE. LF, low-fat diet; HF, high-fat-high-sucrose diet; DR, diet-induced obesity-resistant group; DIO, diet-induced obesity-prone group; CO₂, rate of CO₂ production; O₂, rate of oxygen production; RQ, respiratory quotient; MR, metabolic rate.

[Fᵣ(4,42) = 10.49 P < 0.001], with levels of rO₂ and rCO₂ increasing in the LF group, whereas they were reduced in the HF-fed groups. A similar time × group interaction effect was observed on MR [Fᵣ(4,42) = 5.60, P < 0.01], with MR going up in the LF group and down in the HF-fed groups. Between-group effects on MR did not reach statistical significance. When body mass was added as covariate, we observed a similar time × group interaction [Fᵣ(4,42) = 4.27, P < 0.01]. Between-subject analysis revealed a lower MR in the HF-DR group compared with the HF-DIO and LF groups [Fᵣ(2,20) = 5.98, P < 0.01]. The RQ was affected by group [Fᵣ(2,21) = 42.03, P < 0.001], with both HF-fed groups having a lower RQ than the LF group.

**Isotope equilibration and body composition.** Blood isotopic enrichments (Eᵢᵣᵣ) of 2H and 18O at 1, 2, and 3 h after injection of the DLW mixture are presented in Fig. 1, bottom left and bottom right, respectively. RM-ANOVA revealed a significant time × group interaction effect on Eᵢᵣᵣ 2H and 18O [for 2H, Fᵣ(4,42) = 5.45 P < 0.01; for 18O, Fᵣ(4,40) = 3.50 P < 0.05], with those in the HF-DIO mice being lowest and those in the LF-fed mice highest. Furthermore, Eᵢᵣᵣ was generally highest at the 2- or 3-h time point, with the 1st hour clearly being lower than the 2nd and 3rd hours for both 18O and 2H. The Eᵢᵣᵣ 18O/2H ratio showed a significant time × group interaction [Fᵣ(4,40) = 4, 90, P < 0.01; data not shown], with that of the HF-fed groups decreasing significantly over time. The LF group showed only a modest decrease in the Eᵢᵣᵣ 18O/2H ratio over the 2nd and 3rd hours (data not shown).

**Initial isotope dilution spaces and body composition.** Dilution spaces (N) were calculated at 1, 2, and 3 h after DLW injection by applying the plateau method as well as the intercept method for both 2H and 18O. Only those calculated by the intercept method using a fixed time point for the final at 24 h are shown in Fig. 2, top left. Those calculated by the plateau method yielded similar interactions and differences.

HF-DIO mice had the highest NO (ND) showed similar differences) at the different time points and the LF-fed mice the lowest NO. When 1-h initials of 18O (2H yielded similar results) were used for the determination of NO by the plateau method, they yielded an ∼12% higher value than values calculated from the 2nd- or 3rd-hour initial in the HF-fed groups (see Fig. 2, top left). In the LF group, the difference between 1 and 2-to 3-h initial NO was only ∼2% [time × group Fᵣ(4,40) = 4.25, P < 0.01].

Dilution space ratios (ND/NO) ranged from 0.99 to 1.04 for the plateau method and from 1.02 to 1.07 for the intercept method. RM-ANOVA on ND/NO ratios obtained by the plateau method (see Fig. 2, top right) revealed a significant effect of time [Fᵣ(2,40) = 72, P < 0.001] and group [Fᵣ(2,20) = 5, P < 0.05]. Post hoc analysis revealed that HF-fed mice had significantly lower NO/NO than LF-fed mice. There was no effect of time on ND/NO calculated by the intercept approach, but group differences for NO/NO persisted [Fᵣ(2,20) = 10.9, P < 0.001]. Overall NO/NO calculated by the intercept method was 4–5% higher than that calculated by the plateau method.
The body water pool assessed by carcass analysis in HF-DIO and HF-DR mice (following desiccation and soxhlet fat extraction), expressed as percentual deviation from the body water pool estimated by $^{18}$O dilution, is shown in Fig. 2. Deviations are shown with initials taken at 1, 2, and 3 h and using the “plateau” (Fig. 2, bottom left) and “intercept” method, using the final on day 3 (Fig. 2, bottom right). $E_{\text{ini}}$ $^{18}$O at 1 h resulted in an ~20% overestimation of body water pool relative to the level obtained by the desiccation method. This difference was smaller at 2 and 3 h, particularly when the intercept method level obtained by the desiccation method. This difference was investigated by using the enrichment levels of $^{18}$O and $^2$H at the same final point (we chose the final on day 3 (Fig. 2, bottom right)). $E_{\text{ini}}$ $^{18}$O at 1 h resulted in an ~20% overestimation of body water pool relative to the level obtained by the desiccation method. This difference was smaller at 2 and 3 h, particularly when the intercept method was used. None of these levels were different between HF-DIO and HF-DR mice.

*Isotope turnovers.* Turnover rates of $^{18}$O ($k_O$) and $^2$H ($k_D$) calculated from logarithmic decline using initials and finals were used for calculation of $rCO_2$ (from $k_O - k_D$) and for assessment of the body water flux linked to oxygen turnover (by $k_D/k_O$) in the different experimental groups, and these are shown in Fig. 3.

First, the relevance of the initial time points (i.e., at 1, 2, and 3 h) for $k_O - k_D$ and $k_D/k_O$ in the different diet groups was investigated by using the enrichment levels of $^{18}$O and $^2$H at the same final point (we chose day 2). As shown in Fig. 3, *top left*, there was no significant time effect or time × group interaction effect on $k_O - k_D$ values, but a tendency ($P = 0.066$) was observed for a group effect, meaning that $k_O - k_D$ levels tended to be higher in LF-fed mice than in the HF-fed mice.

Analysis of $k_D/k_O$ values revealed a significant group × time interaction ($F_{(4,40)} = 5.88, P < 0.001$; Fig. 3, *top right*). This effect was caused mainly by the difference at the 1st hour, during which the ratio for the HF-fed mice was ~27% lower than at 2 and 3 h. This difference was much smaller in the LF group (at the 1st hour, ~4% lower than at 2 h). There was no significant interaction anymore if 1-h ratio was excluded from the model, indicating no significant difference between 2- and 3-h ratios. Between-group differences persisted over the 3-h period, showing consistently that HF-fed mice overall had a lower $k_D/k_O$ ratio than LF-fed ones, irrespective of weight gain.

Next, we evaluated the effect of the duration of the time interval between initial and final (i.e., taken at 1, 2, and 3 days) on $k_O$ and $k_D$, and thus the resultant $k_O - k_D$ and $k_D/k_O$, using one initial time (2 h). In the analysis of $k_O - k_D$ from aforementioned time points, a significant time × group interaction [$F_{(2,20)} = 11.81, P < 0.001$] was observed (see Fig. 3, bottom left). In both HF-fed groups, $k_O - k_D$ decreased over the course of the 3-day measurement, whereas in LF-fed mice $k_O - k_D$ increased.

Analysis of $k_D/k_O$ showed a group effect [$F_{(2,20)} = 9.34, P < 0.01$] and no difference over the 3 days, with LF-fed mice having overall a significantly higher $k_D/k_O$ than the HF-fed DR and DIO mice (Tukey-HSD, $P < 0.01$; see Fig. 3, bottom right).

**Different methods of calculation.** Several equations shown in Table 1 were used to calculate $rCO_2$, using the 2-h initials. The results, by using the 2-h initials and 2-day finals, are shown in Fig. 4 together with the results of indirect calorimetry. Although the DLW method performed well in the LF group, we observed a significant deviation from the actual $rCO_2$ based on indirect calorimetry, with DLW systematically overestimating $rCO_2$ by ~18% (depending on the type of equation and model) in the HF-fed mice irrespectively of body composition. In general, one-pool model equations performed worse than two-pool model ones. Within the DLW results, neither using any of the models nor using intercept or plateau made a significant difference (that is, significant compared with the SE; see Fig. 4). This shows that the DLW method in itself is robust. Nevertheless, it can apparently deliver results that are systematically deviating.

Finally, the multisample approach did not perform better than a two-sample approach when using the initial at 2 h. Differences over 3 days between the two approaches for calculating decay rates were small (<1%).

**Duration of the measurement.** To evaluate the effect of time between sampling of initial and final enrichments and how this influenced the validity of $rCO_2$ by DLW analysis (i.e., compared with $rCO_2$ production assessed by indirect calorimetry), we examined deviations from the latter by using Supplemental Table S1, Eq. 5, and the 2-h initial on each day of the DLW

![Fig. 3. Comparison of $k_O - k_D$ (left) or $k_D/k_O$ (right) between having different initials (top) and different duration between measurements (bottom) in HF-fed DIO (black bar) and DR mice (gray bar) and in LF-fed (open bar) mice. Data are expressed as means ± SE; Tukey’s post hoc test. *LF vs. HF-DR or HF-DIO.](image-url)
experiment. We used the plateau as well as the intercept method to evaluate body water pool. Results are presented in Table 2. However, the averaged analytical error decreased after each day of measurement (−3% on day 1, −1.5% on day 2, and −1% on day 3). When the plateau method was used for estimation of the body water pool, RM-ANOVA showed a significant time × group interaction [F(4,40) = 8.25, P < 0.001]. Deviation from rCO2 assessed by indirect calorimetry increased after each day of measurement in the HF-fed group, whereas it changed within the margin of the analytical error in the LF-fed group. In the LF group, the deviation of estimated rCO2 from the actual one decreased significantly on day 3, whereas it changed within the margin of the analytical error in the HF-fed group. When we analyzed the equilibration period during the 3 h after isotope administration, we observed an incomplete mixing of the labels, in particular in the HF-fed group, with 1 h being significantly lower in the HF group than in the LF group. It may be possible that the incomplete mixing persisted at 2 and 3 h, which caused overestimation of the body water pool and thus overestimation of rCO2. In the validation study performed by Schoeller et al. (30), similar incompleteness in the equilibration of the labels was observed in obese human subjects. In that study, in lean subjects a stable equilibration was reached between 2 and 6 h after isotope administration, whereas in obese subjects the estimates were more variable, and the same degree of stability was not obtained before 5 h postdosing.

Verification by carcass analysis through desiccation showed an overestimation of body water by DLW, particularly when the initial at 1 h was used for the calculation of total body water. This difference occurred at 2 and 3 h as well, but to a minor extent. This comparison also showed that the intercept method performed better at longer initial final intervals in determination of body water (from 10 to 5% deviation at 2 and 3 h) than the plateau method.

One possible cause of the overestimation of the body water pool is that hydrogen and/or oxygen can be incorporated into nonaqueous molecules and/or excreted from the body independent of CO2 and water fluxes. In addition to the increase in body water pool, the dilution space ratio of deuterium and oxygen (N/D/N) was lower in the HF-fed mice than in the LF-fed mice. Because N/D/N tended to be lower only in the

### Table 2. Percentual deviation of rCO2 assessed by the DLW method relative to rCO2 assessed by indirect calorimetry during 3-day measurement, using Eq. 5 in Supplemental Table S1 and the initial taken at 2 h postenrichment, using either the plateau or the intercept method

<table>
<thead>
<tr>
<th>Method</th>
<th>Day 1</th>
<th>Day 2</th>
<th>Day 3</th>
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</thead>
<tbody>
<tr>
<td>Plateau</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LF</td>
<td>−0.5 ± 1.1</td>
<td>3.9 ± 1.5</td>
<td>−5.7 ± 2.4</td>
</tr>
<tr>
<td>HF-DR</td>
<td>19.5 ± 2.9</td>
<td>25.8 ± 2.8</td>
<td>39.6 ± 6.2</td>
</tr>
<tr>
<td>HF-DIO</td>
<td>21.3 ± 3.3</td>
<td>23 ± 2.1</td>
<td>33.0 ± 4.4</td>
</tr>
<tr>
<td>Interceptor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LF</td>
<td>−3.3 ± 1.0</td>
<td>0.8 ± 1.5</td>
<td>−1.4 ± 1.8</td>
</tr>
<tr>
<td>HF-DR</td>
<td>16.7 ± 2.7</td>
<td>23.0 ± 2.7</td>
<td>18.9 ± 2.1</td>
</tr>
<tr>
<td>HF-DIO</td>
<td>18.7 ± 3.2</td>
<td>20.2 ± 2.1</td>
<td>17.0 ± 1.7</td>
</tr>
</tbody>
</table>

Data are expressed as means ± SE. DLW, doubly labeled water.

The most important finding here is that an excellent match existed between rCO2 assessed by the two methods in the LF-feeding mice, whereas there was a consistent overestimation of rCO2 by the DLW technique in the HF-fed animals compared with actual CO2 production. This was already anticipated because several other studies in mammals validating the DLW technique reported such overestimation, as reviewed by Speakman and Racey (34) in 1988 and later by others (10, 33). The importance of our study is that feeding a HF diet may be a relevant factor in explaining this inconsistency rather than the increased amount of body fat (or any other compartment associated with this) induced by HF feeding in the DIO-prone mice. DLW studies performed thus far have ignored nutritional or body composition effects on the validity of the rCO2 assessed by DLW method.

A number of factors may have contributed to this error. When we analyzed the equilibration period during the 3 h after administration of the labels, we observed an incomplete mixing of them, particularly in the HF-fed group, with 1 h being significantly lower in the HF group than in the LF group. It may be possible that the incomplete mixing persisted at 2 and 3 h, which caused overestimation of the body water pool and thus overestimation of rCO2. In the validation study performed by Schoeller et al. (30), similar incompleteness in the equilibration of the labels was observed in obese human subjects. In that study, in lean subjects a stable equilibration was reached between 2 and 6 h after isotope administration, whereas in obese subjects the estimates were more variable, and the same degree of stability was not obtained before 5 h postdosing.

Verification by carcass analysis through desiccation showed an overestimation of body water by DLW, particularly when the initial at 1 h was used for the calculation of total body water. This difference occurred at 2 and 3 h as well, but to a minor extent. This comparison also showed that the intercept method performed better at longer initial final intervals in determination of body water (from 10 to 5% deviation at 2 and 3 h) than the plateau method.

One possible cause of the overestimation of the body water pool is that hydrogen and/or oxygen can be incorporated into nonaqueous molecules and/or excreted from the body independent of CO2 and water fluxes. In addition to the increase in body water pool, the dilution space ratio of deuterium and oxygen (N/D/N) was lower in the HF-fed mice than in the LF-fed mice. Because N/D/N tended to be lower only in the
HF-DIO vs. the HF-DR mice, this points toward primary dietary effects on N/D, but body composition effects may be not ruled out. Thus, the estimated turnover of hydrogen was too low, the estimated turnover of oxygen was too high, or both processes occurred simultaneously. One potential mechanism is that the HF-fed mice have a lower level of hydrogen and methane production by gut microbiota as a result of lower dietary fiber density than the LF-fed mice, which is analogous to what has been found in humans and pigs (13, 22). In turn, this then would lead to a relatively lower $^2$H turnover in the HF-fed mice than in the LF-fed mice. Another potential mechanism contributing to fluxes independent from water and CO$_2$ is an elevated level of ketone body production by HF feeding. Normally, ketone bodies are produced during fasting as a side effect of $\beta$-oxidation, which can be used as an alternative substrate in the brain. Several studies have shown that the feeding of a HF diet will also lead to an upregulation of the production of ketone bodies (5, 6, 15, 25), and when not sufficiently metabolized they will accumulate in the urine or breath because these fuels are water soluble (6). The net loss of ketone bodies will constitute an increased $^{18}$O flux from the body independent of CO$_2$ and water turnover. Of course $^2$H is dragged along in this process, but in a smaller proportion to $^{18}$O in ketones compared with water. $^{18}$O and $^2$H fluxes could also be increased due to incorporation of these molecules in urea via the ornithine-arginine synthesis cycle. This effect may be substantial if the HF-fed mice have an increased extent of protein degradation and urea synthesis (7, 35). At present, it is extremely difficult to make summated numerical estimates to the extent by which all of these pathways contribute to $^{18}$O and $^2$H turnovers beyond those mediated by CO$_2$ and water turnover. A final, even more exotic explanation of which very little is known is that isotopic levels of H and O atoms in intracellular water could differ from the extracellular compartment by physiological processes that discriminate between isotopes (16, 17). The latter processes could potentially explain differential intra/ extracellular isotopic composition and could be underlying to the differences in the N/D $^{18}$O ratio in the HF-fed mice relative to the LF-fed mice.

In summary, our data showed that, compared with actual rCO$_2$, the DLW method performed extremely well when rCO$_2$ in the LF-fed mice was assessed with a precision of $-0.5 \pm 1.1$ (considering an analytical error of $\sim 1.5\%$). Furthermore, the intercept method appears to perform superiorly over the plateau method in estimating isotopic pool sizes, in particular for longer measurement duration (i.e., 3 days). We did not observe a significant improvement in the multismap approach over the two-sample one. We recommend particular caution with the use of the DLW technique in HF-fed humans and animals because it may overestimate MR calculated by DLW. These findings can have major consequences for the interpretation of results obtained by the DLW technique, particularly in obesity research. Future research should be dedicated to the mechanisms (of which potentially some are mentioned above) underlying this discrepancy and how to correct for it.

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DISCLOSURES

The authors declare no conflicts of interest, financial or otherwise.

AUTHOR CONTRIBUTIONS

S.G., H.A.J.M., and G.v.D. contributed to the conception and design of the research; S.G. performed the experiments; S.G. analyzed the data; S.G. and G.v.D. interpreted the results of the experiments; S.G. prepared the figures; S.G. drafted the manuscript; S.G., H.A.J.M., and G.v.D. edited and revised the manuscript; S.G., H.A.J.M., and G.v.D. approved the final version of the manuscript.

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