Assessment of physical activity in older individuals: a doubly labeled water study

RAYMOND D. STARLING,1 DWIGHT E. MATTHEWS,1 PHILIP A. ADES,2 AND ERIC T. POEHLMAN1

Departments of 1Clinical Pharmacology and Metabolic Research and 2Cardiology, Department of Medicine, University of Vermont, Burlington, Vermont 05405

The development of doubly labeled water (DLW) methodology has provided a unique opportunity to examine the accuracy of commonly used physical activity instruments (20). Physical activity energy expenditure can be estimated by determining the difference between total daily energy expenditure (TEE) measured by DLW and resting metabolic rate (RMR) and thermic effect of food measured by indirect calorimetry. This stable-isotope approach requires little subject cooperation, is unobtrusive, and measures free-living activity throughout a person's daily routine. Unfortunately, the relatively high price of the oxygen-18 water, mass spectrometer instrumentation, and the need for technical expertise in sample preparation and measurement have limited its widespread application. Nevertheless, DLW appears to be a gold standard for validating other methods to measure daily physical activity energy expenditure in free-living individuals (11).

It was our aim to examine the accuracy of several methods to measure daily physical activity energy expenditure in free-living older individuals. Specifically, we assessed physical activity in older women and men using the following methods: 1) Minnesota Leisure Time Physical Activity Questionnaire (LTA), 2) Yale Physical Activity Survey (YPAS), 3) Caltrac uniaxial accelerometer, and 4) DLW and indirect calorimetry. The Minnesota LTA was chosen because it is one of the most commonly used physical activity interview methods (24), although few studies have directly compared it with DLW. The YPAS is a newly developed interview method for older individuals that has not been directly compared with DLW (6). The Caltrac uniaxial accelerometer has gained some degree of popularity as an instrument to measure physical activity; however, it has not been critically examined against DLW in older individuals.

MATERIALS AND METHODS

Subjects

Research volunteers were healthy, older Caucasian women (n = 35) and men (n = 32), between 45 and 84 yr of age, recruited from the greater Burlington, VT area. All participants were healthy and had no history or evidence on physical examination of 1) coronary heart disease (e.g., S-T segment depression >1 mm at rest or exercise); 2) hypertension (resting blood pressure >140/90); 3) medications that could affect cardiovascular function or metabolism; 4) diabetes; 5) body mass fluctuation of >2 kg over the past year; 6) exercise-limiting noncardiac disease (arthritis, peripheral vascular disease, cerebral vascular disease); or 7) smoking. Subjects were physically active but not participating in a structured aerobic or resistance-training program. Addition-
ally, subjects had not experienced major lifestyle changes over the past 12 mo before testing. Each subject signed a consent form approved by the Institutional Review Board of the University of Vermont before participating in the study.

Testing Protocol

Data were collected during an overnight stay in the General Clinical Research Center (GCRC) at the University of Vermont. Subjects were dosed with DLW, and the Minnesota LTA and YPAS was administered the evening of the overnight stay. RMR, body composition via dual-energy X-ray absorptiometry, and treadmill aerobic capacity were assessed the following morning. Subjects returned 10 days later to provide final urine samples for the DLW measurement. The Caltrac was worn during this 10-day outpatient period. Specific details about all testing are provided in Physical Activity Assessment.

Physical Activity Assessment

DLW. DLW, in conjunction with indirect calorimetry, was used to measure free-living, physical activity energy expenditure. TEE was determined from DLW over a 10-day period. RMR was determined from 45 min of indirect calorimetry. The following equation was used to calculate daily physical activity energy expenditure (in kcal/day): (TEE × 0.9) – RMR. This approach assumed that the thermic effect of feeding is 10% in the elderly (16). Specific details about all DLW and indirect calorimetry methodologies are provided below.

DLW procedures used in our laboratory have been described extensively elsewhere (23). Between 1200 and 1600, a premixed dose containing 0.078 g of $^2$H$_2$O and 0.092 g of $^{18}$O was administered to each subject to measure TEE over a 10-day period using the method of Schoeller and van Santen (20). One urine sample was collected before dosing, two the following morning, and two samples 10 days later. Samples were frozen at −20°C in vacuum until later analysis for $^2$H and $^{18}$O enrichments by isotope ratio mass spectrometry. $^{18}$O isotopic enrichments were determined from the CO$_2$ equilibration technique, and $^2$H enrichments were determined by the zinc catalyst method of Wong et al. (29). Rate of CO$_2$ production ($r_{CO_2}$, in mol/day) was calculated by using Eq. 3 of Speakman et al. (22): $r_{CO_2} = \frac{N}{2.196} \times (c_{K_2} - c_{K_1})$, where $N$ is total body water, $c_k$ and $k_k$ are the elimination rates of $^{18}$O and $^2$H tracers from the body, and $c_{K_2}$ and $c_{K_1}$ are the dilution spaces for $^{18}$O and $^2$H tracers, respectively, as recommended by Racette et al. (17). Assuming a respiratory quotient of the food consumed of 0.85 (1), total CO$_2$ production was converted to TEE (kcal/day) by using the Weir formula (27).

RMR was measured by indirect calorimetry by using the ventilated hood technique (15) after an overnight 12-h fast in the GCRC. Respiratory-gas analysis was performed by using a Deltrac metabolic cart (Sensormedics, Yorba Linda, CA). RMR (kcal/day) was calculated from the equation of Weir (27). The test-retest correlation coefficient within 1 wk has been shown to be 0.90 for RMR in our laboratory.

Caltrac. Physical activity energy expenditure was determined from a Caltrac uniaxial accelerometer (Muscle Dynamics Fitness Network, Torrance, CA). This accelerometer was worn during all waking hours over a 9-day period. An accelerometer was firmly attached to a belt or the waistband of the subject’s clothing, directly inferior to the greater trochanter. This accelerometer has a ceramic piezoelectric transducer that detects vertical displacement, and this signal is translated into a total activity energy count per day (28). The Caltrac accelerometer measures walking and running activity energy expenditure, in addition to calculating non-weight-bearing activities, such as weight lifting, bicycling, rowing, and strenuous upper body motions, by using unpublished correction factors. All accelerometers were concurrently agitated with a mechanical shaker under standardized conditions over a 24-h period, and those accelerometers with activity energy counts >2.5% of the mean reading for the group were not used. The test-retest correlation coefficient has been shown to be 0.98 for the Caltrac in older women and men (12). Average daily physical activity energy expenditure (kcal/day) over the 9-day measurement period was used for data analyses.

Minnesota LTA. Leisure-time physical activity was measured by the Minnesota LTA (24). This is a commonly used, interviewer-administered questionnaire that assesses daily physical activity accumulated during leisure time and household activities over the past 12 mo. Trained personnel administered the questionnaire during a 20-min interview. Leisure-time physical activity was calculated based on the number of months spent completing the specific activity per year, average number of times for the specific activity each month, total time per each specific activity session, and an activity-specific intensity code. The test-retest correlation coefficient over a month has been shown to be 0.92 in 20- to 59-yr-old women and men (19). Average daily physical activity energy expenditure (kcal/day) for the 12-mo period was used for data analyses.

YPAS. Physical activity energy expenditure was also determined by using the YPAS, which is a recently developed interviewer-administered questionnaire for the elderly (6). This questionnaire assesses a typical week of activity in the last month and examines household, exercise, and recreational activities. The survey was administered during a 20-min interview by the same trained person who administered the Minnesota LTA. Physical activity expenditure was calculated based on total time per week in each specific activity and the same activity-specific intensity code used in the Minnesota LTA. The test-retest correlation coefficient over 2 wk has been shown to be 0.42–0.65 in 71-yr-old women and men (6). Average weekly physical activity energy expenditure was converted to a daily value (kcal/day) for data analyses.

Statistical Analyses

All data are expressed as means ± SD. First, potential differences among the methods to measure physical activity (i.e., DLW, Caltrac, YPAS, and LTA) were determined for women and men by using a repeated-measures analysis of variance (gender × activity method). If a significant main effect or interaction was detected, Tukey’s post hoc test was used to determine specific differences. Additionally, to account for the influence of body mass on physical activity energy expenditure, DLW data were adjusted for body mass by using partial correlation analysis, as previously suggested (4). Significance was accepted at the P < 0.05 level.

Second, agreement between DLW and the three alternative methods to measure physical activity was also examined by using Bland and Altman analyses (2). Specifically, individual comparisons between DLW and the alternative methods were completed by examining a plot of the difference in physical activity between DLW and the alternative method vs. mean physical activity determined from DLW. From these data, limits of agreement between DLW and the alternative method were calculated (i.e., mean difference between DLW and the alternative method ± 2 SD of the difference). A narrow limits of agreement (i.e., ±50–100 kcal/day) would
suggestion that we could confidently use the alternative method as a proxy of DLW to measure physical activity.

RESULTS

Descriptive characteristics for all subjects are presented in Table 1. The older women and men participating in this study ranged in age from 45 to 84 yr, were lean to moderately overweight, and had low-to-moderate cardiorespiratory fitness. As expected, the men were taller, heavier, and had more lean tissue mass and less fat mass than did the women.

Daily physical activity energy expenditure data are presented in Fig. 1 for women and men. Women had lower physical activity energy expenditure irrespective of assessment method. For older women, physical activity energy expenditure measured by LTA (386 ± 228 kcal/day) and Caltrac (379 ± 162 kcal/day) was significantly lower than that measured by DLW (873 ± 244 kcal/day) and the YPAS (863 ± 447 kcal/day). No difference was present between DLW and YPAS for women. For older men, physical activity energy expenditure measured by LTA (459 ± 288 kcal/day) and Caltrac (554 ± 242 kcal/day) was significantly lower than that measured by DLW (1,211 ± 429 kcal/day) and the YPAS (1,107 ± 612 kcal/day). No difference was present between DLW and YPAS for men.

Bland and Altman data are presented in Fig. 2 for women and Fig. 3 for men. The limits of agreement were wide for the Minnesota LTA (−211 to +1,185 kcal/day), YPAS (−963 to +981 kcal/day), and Caltrac (+75 to +911 kcal/day) in women. The limits of agreement were also wide for the Minnesota LTA (−220 to +1,724 kcal/day), YPAS (−1,310 to +1,518 kcal/day), and Caltrac (−96 to +1,408 kcal/day) in men. Adjusting DLW data for body mass did not significantly change the analysis of variance or Bland and Altman results (data not shown).

DISCUSSION

We examined the accuracy of several commonly used methods to measure daily physical activity energy expenditure in older Caucasian women and men using DLW in conjunction with indirect calorimetry as the criterion measure. Our data suggest that the Minnesota LTA recall and Caltrac uniaxial accelerometer significantly underestimate free-living physical activity energy expenditure in older women and men. Although the YPAS compares favorably with DLW on a group basis, its use as a proxy measure of individual daily physical activity energy expenditure may be limited in older women and men.

Minnesota LTA

The Minnesota LTA recall has been used extensively in physical activity research (24). Despite this recall questionnaire being inexpensive, relatively easy to administer, and unobtrusive to the subject, its accuracy has not been extensively examined against DLW. Our results demonstrate that the Minnesota LTA underestimates total daily physical activity energy expenditure by 56% in older women and 62% in older men compared with DLW (see Fig. 1). Furthermore, the limits of agreement from Bland and Altman analyses (see Figs. 2 and 3) demonstrated wide ranges of agreement between DLW and the Minnesota LTA for both older women (−211 to +1,185 kcal/day) and men (−220 to +1,724 kcal/day). These findings are consistent with recent work that showed the Minnesota LTA underestimates physical activity compared with DLW in older clairaudients (8). In contrast, previous work from Goran and Poehlman (10) demonstrated a strong, simple correlation between DLW and the Minnesota LTA (r = 0.83; P < 0.0001) in 13 older women and men; however, these results are limited because of the small mixed-gender sample and the fact that a strong bivariate relationship does not necessarily imply agreement between the two methods (2)

The Minnesota LTA was developed in men ~40–60 yr of age, which may partially explain why it underestimated physical activity in our older cohort (45–84 yr of

![Fig. 1. Daily physical activity energy expenditure measured by doubly labeled water (DLW), Yale Physical Activity Survey (YPAS), Minnesota Leisure Time Physical Activity Questionnaire (LTA), and Caltrac for 35 older women and 32 older men. *P < 0.05 compared with DLW.](http://jap.physiology.org/DownloadedFromhttp://jap.physiology.org/)

### Table 1. Descriptive characteristics of older women and men

<table>
<thead>
<tr>
<th>Variable</th>
<th>Women</th>
<th>Men</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>35</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>Age, yr</td>
<td>67 ± 9</td>
<td>66 ± 11</td>
<td>0.83</td>
</tr>
<tr>
<td>Height, cm</td>
<td>160.4 ± 6.7</td>
<td>175.8 ± 6.4</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Body mass, kg</td>
<td>63.9 ± 10.2</td>
<td>79.5 ± 14.5</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Body mass index, kg/m²</td>
<td>24.8 ± 3.9</td>
<td>25.7 ± 4.5</td>
<td>0.39</td>
</tr>
<tr>
<td>Lean tissue mass, kg</td>
<td>36.4 ± 3.9</td>
<td>58.3 ± 6.9</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Fat mass, kg</td>
<td>22.0 ± 8.2</td>
<td>16.3 ± 8.1</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Body fat, %</td>
<td>35 ± 8</td>
<td>21 ± 7</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>V_{O_2}max, l/min</td>
<td>1.96 ± 0.84</td>
<td>2.27 ± 0.88</td>
<td>0.31</td>
</tr>
</tbody>
</table>

*Values are means ± SD. V_{O_2}max, maximal O² uptake of treadmill aerobic capacity adjusted for lean tissue mass using analysis of covariance (25). Body composition was assessed by dual-energy X-ray absorptiometry.*
Age-neutral recall questionnaires, such as the Minnesota LTA, have been shown to underestimate physical activity in older individuals (26). Along these lines, Richardson et al. (19) recently demonstrated in 20- to 59-yr-old women and men that the Minnesota LTA underestimated low- to moderate-intensity activities, inaccurately assessed walking activities, and omitted certain activities. Furthermore, the Minnesota LTA recall may not be suitable for older individuals because 1) it focuses on team sports and higher intensity activities, in which many older individuals do not participate (5), and 2) accurate recall of activities over the past 12 mo may be difficult for some older individuals. Overall, our data suggest that the 12-mo Minnesota LTA recall may substantially underestimate daily physical activity energy expenditure in older women and men.

YPAS

There are few recall questionnaires specifically developed for the elderly and directly validated in an independent cohort. Of those questionnaires available (13), the accuracy of daily physical activity energy expenditure measured by the YPAS (6) has not been compared with DLW. Our data demonstrate that daily physical activity energy expenditure measured by the YPAS for a group of older women and men accurately reflects the mean values determined from DLW (see Fig. 1). However, the limits of agreement from Bland and Altman analyses...
(see Figs. 2 and 3) were wide for women (−963 to +981 kcal/day) and men (−1,310 to +1,518 kcal/day), suggesting that the YPAS may not be a suitable proxy measure of physical activity in older individuals.

The YPAS was formulated from interviews of >200 healthy, older women and men (60+ yr of age), which may increase its accuracy to detect group physical activity levels in older individuals. Moreover, this recall questionnaire captures low- to higher intensity activities commonly engaged in by older individuals, including housework, yard work, caretaking, structured exercise, and leisure-time activities. Furthermore, physical activity is assessed during a typical week over the past month, which may decrease the chance of memory-recall errors. The present data corroborate with those of Campbell et al. (3), who used the energy intake/balance method in conjunction with indirect calorimetry to measure physical activity in nine older women. Thus we suggest that the YPAS may be an accurate method to quantify daily physical activity energy expenditure in groups of older women and men. These results are interesting because the YPAS was developed as an epidemiology tool to rank individuals and not to determine absolute physical activity levels (L. DiPietro, personal communications). Despite the concordance of the YPAS with DLW on a group-mean basis, its usefulness to measure individual physical activity energy expenditure, particularly before and after clinical inter-

Fig. 3. Bland and Altman plots between DLW and Caltrac (A), Minnesota LTA (B), and YPAS (C) for 32 older men. Mean difference between DLW and the alternative method ± 2 SD are shown.
Physical activity assessment in older individuals

Despite the widespread use of the Caltrac uniaxial accelerometer over the last 15 yr, few studies have examined its accuracy against stable isotope-derived assessments of physical activity. Our data demonstrate that Caltrac underestimates daily physical activity energy expenditure, compared with DLW, by 50–55% in older women and men (see Fig. 1). Although the limits of agreement from Bland and Altman analyses (see Figs. 2 and 3) for older women (+75 to +911 kcal/day) and men (−96 to +1,408 kcal/day) were narrower than those for the Minnesota LTA and YPAS, the limits were still quite wide to suggest good agreement with DLW for measurement of physical activity. Collectively, these data suggest that a Caltrac uniaxial accelerometer may not be suitable for determining physical activity levels in older individuals.

Our results contrast with those in younger obese women (7) and older claudients (8). A possible explanation is that the Caltrac may determine physical activity more accurately in these populations that have low activity levels and may lose its sensitivity to measure activity in a more active cohort, such as individuals in the present study. Furthermore, underestimation of physical activity energy expenditure by the Caltrac may be partially due to its inability to capture a variety of nonwalking activities such as swimming, detect motion other than that occurring in the vertical plane, and measure postexercise energy expenditure (11). The presently used Caltrac has been modified to reduce underestimation by including unpublished equations to estimate nonwalking activities such as cycling, rowing, weight lifting, and upper body motions. Despite this modification, the Caltrac uniaxial accelerometer may not accurately measure daily physical activity energy expenditure in older women and men. Future studies may need to assess the accuracy of a triaxial accelerometer in the elderly to determine whether this three-plane motion detector can capture lower intensity activities and activities in which older individuals commonly participate.

Study Strengths and Limitations

A limitation of the present study is the inability to generalize these results to older individuals with known disease, which may inhibit their participation in physical activity. Furthermore, in addition to capturing volitional activity energy expenditure (e.g., walking, cycling, daily occupational and household tasks), DLW, in conjunction with indirect calorimetry, measures nonvolitional activity energy expenditure, such as fidgeting, which may contribute 100–800 kcal/day (18). The inability of recall methods and accelerometers to detect fidgeting may partially contribute to the underestimation of physical activity in the present study. Moreover, although DLW, Caltrac, and YPAS were used to assess a similar time period of physical activity, the Minnesota LTA assessed the past 12 mo, which may have caused an underestimation, particularly if physical activity measured by DLW was relatively high during the 10-day period. The 4-wk modified Minnesota LTA may partially reduce this potential bias (19). Even though we anticipated that the presently examined methods would underestimate physical activity, the magnitude of the underestimation was surprising as was the poor lack of agreement between the methods.

The major strength of the present study is the direct measurement of daily physical activity energy expenditure in older individuals with the use of DLW in conjunction with indirect calorimetry. Although our sample size was small compared with that of epidemiology-based research, the present sample is relatively large for studies that use DLW. Furthermore, this is one of the first studies to comprehensively compare the accuracy of commonly used but nonvalidated methods of measuring physical activity in older individuals.

Summary

Our data suggest that the Minnesota LTA recall and Caltrac uniaxial accelerometer may significantly underestimate free-living physical activity in older women and men. In contrast, the YPAS compares favorably with DLW on a group basis, although wide limits of agreement suggest that its use as a proxy measure of individual daily physical activity energy expenditure may be limited in older women and men. It is important for future studies to use a combination of presently available physical activity methods and/or develop new inexpensive but accurate methods to capture physical activity levels of older individuals.

We express our appreciation to Amy N. Turner and Christine A. Potter for technical assistance and to all participants who volunteered for the study.

This project was supported in part by National Institute on Aging Grant F 32-AG-05791 (to R. D. Starling), National Institute of Diabeties and Digestive and Kidney Diseases Grant DK-52752 (to E. T. Poehlman), and General Clinical Research Center at the Univ. of Vermont Grant RR-00105.

Address for reprint requests and other correspondence: E. T. Poehlman, Univ. of Vermont, Dept. of Medicine, Given Bldg. C-247, Burlington, VT 05405 (E-mail: epoehlma@uvm.edu).

Received 5 November 1998; accepted in final form 29 January 1999.

REFERENCES


