PAPER

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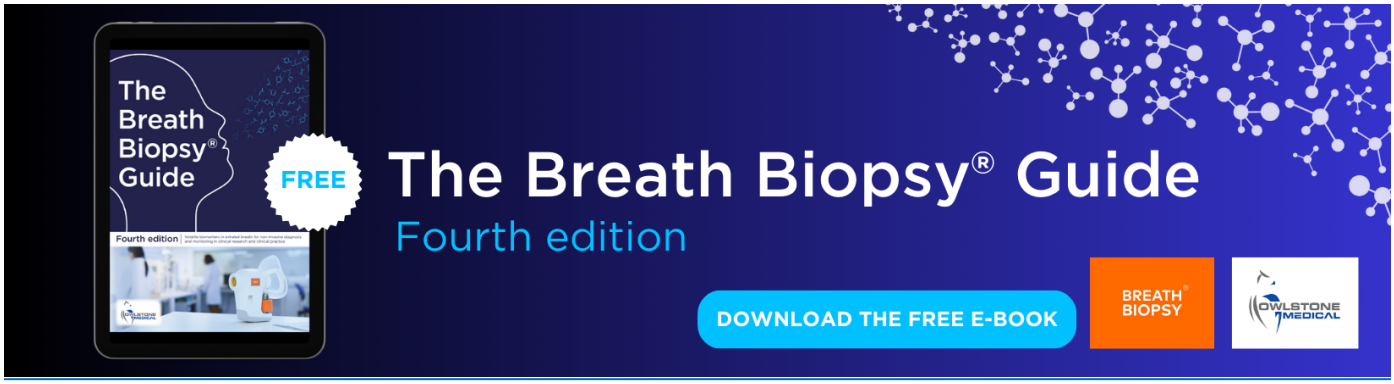

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PAPER

Effectiveness of breath acetone monitoring in reducing body fat and improving body composition: a randomized controlled study

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Abstract

When attempts to lose body fat mass frequently fail, breath acetone (BA) monitoring may assist fat mass loss during a low-carbohydrate diet as it can provide real-time body fat oxidation levels. This randomized controlled study aimed to evaluate the effectiveness of monitoring BA levels and providing feedback on fat oxidation during a three-week low-carbohydrate diet intervention. Forty-seven participants (mean age = 27.8 ± 4.4 years, 53.3% females, body mass index = 24.1 ± 3.4 kg m^{-2}) were randomly assigned to three groups (1:1:1 ratio): daily BA assessment with a low-carbohydrate diet, body weight assessment (body scale (BS)) with a low-carbohydrate diet, and low-carbohydrate diet only. Primary outcome was the change in fat mass and secondary outcomes were the changes in body weight and body composition. Forty-five participants completed the study (compliance rate: 95.7%). Fat mass was significantly reduced in all three groups (all $P < 0.05$); however, the greatest reduction in fat mass was observed in the BA group compared to the BS (differences in changes in fat mass, −1.1 kg; 95% confidence interval: −2.3, −0.2; $P = 0.040$) and control (differences in changes in fat mass, −1.3 kg; 95% confidence interval: −2.1, −0.4; $P = 0.013$) groups. The BA group showed significantly greater reductions in body weight and visceral fat mass than the BS and control groups (all $P < 0.05$). In addition, the percent body fat and skeletal muscle mass were significantly reduced in both BA and BS groups (all $P < 0.05$). However, no significant differences were found in changes in body fat percentage and skeletal muscle mass between the study groups. Monitoring BA levels, which could have motivated participants to adhere more closely to the low-carbohydrate diet, to assess body fat oxidation rates may be an effective intervention for reducing body fat mass (compared to body weight assessment or control conditions). This approach could be beneficial for individuals seeking to manage body fat and prevent obesity.

Abbreviations

BMI	body mass index
BA	breath acetone
BS	body scale
QDs	quantum dots

1. Introduction

The global prevalence of obesity continues to increase, and the fundamental mechanism for its management is the prevention of excessive adipose

tissue accumulation. The accumulation of ectopic lipids in visceral adipose tissue is closely associated with the development of chronic diseases owing to the lipotoxicity released by ectopic lipids, which can induce excessive free fatty acids and inflammatory cytokines [1, 2]. Therefore, promoting lipid oxidation and creating a negative energy balance are key strategies for preventing obesity and subsequent chronic diseases [3]. Although various interventions, including physical activity and dietary modifications, have been examined in the past few decades [4, 5], their effectiveness in clinical practice is unclear. This may be due to the overestimation of energy expenditure from physical activity, the underestimation of energy intake, and/or less sustainable interventions, leading to inconclusive evidence [4].

Measuring exhaled BA is a novel approach to obesity prevention and management, as it provides a noninvasive measure of ketosis [6]. Ketosis is triggered by fasting, caloric restriction, or exercise, which increases the production of ketone bodies as by-products of lipid oxidation [7]. Additionally, a recent review by Anderson [8] suggested that BA levels can be influenced by various factors, including dietary composition, calorie restriction, exercise, and pulmonary factors, all of which can alter fat metabolism. Interestingly, a very low-carbohydrate diet can elevate acetone levels independently of the total energy balance [9]. Furthermore, a low-carbohydrate diet may be more effective than other calorie restriction diet modalities (such as a low-fat or low-glycemic index diet), as it can lead to greater weight loss [10, 11] while maintaining resting energy expenditure [12]. A recent experimental study [13] suggested that a portable BA analyzer could be used as a reliable tool for tracking ketosis dynamics during low-carbohydrate diet interventions.

Effective and sustainable weight loss management is challenging; therefore, developing effective interventions for weight loss and long-term obesity management is critical. Studies have indicated that web-based interventions for weight-loss maintenance programs and continuous real-time feedback using digital technologies for behavioral intervention programs are more effective than control conditions or classical interventions [14–16]. Additionally, daily body weight monitoring can effectively improve weight loss and control [17]. Daily monitoring of body weight can lead to greater adherence to interventions and subsequent weight reduction, which are mediated by a negative energy balance resulting from a restricted diet or increased physical activity [17, 18]. Compliance with weight loss and management intervention programs could potentially be improved if healthcare providers and participants had access to a responsive indicator of fat metabolism on a daily basis [19]. Growing evidence suggests that monitoring BA levels may enhance the effectiveness of lifestyle interventions by indicating real-time energy balance [8, 20, 21]. Using a noninvasive, nonpharmaceutical, simple, and compact portable BA analyzer during lifestyle modifications may be a promising protocol for monitoring body fat burning, which is effective for obesity treatment and management [20, 21].

However, to date, it is elusive whether monitoring BA levels as an intervention is more effective than other interventions with identical lifestyle characteristics for reducing body fat mass and managing weight. Therefore, this study aimed to investigate whether daily feedback on BA is effective in reducing fat mass and improving subsequent body composition. This study compared the effects of BA monitoring feedback and daily monitoring of body weight on fat mass loss under a low-carbohydrate diet intervention condition.

2. Experimental methods

2.1. Study procedure, participants, sample size, and ethics approval

A total of 45 participants participated in this study from May 2021 to August 2021. The sample size was determined using a meta-analysis and review that examined the effects of a low-carbohydrate diet on fat mass changes [22]. The initially calculated sample size of 42 (14 per group) was estimated based on a reported standardized mean difference of 0.82 [22], a two-tailed significance level of 0.05, and a power of 0.8. Considering the potential dropout rate of 10%, a total of 47 participants were recruited. The inclusion criteria for participants were as follows: (1) age between 19 and 40 years (our study limited the upper age of participants to 40 years to ensure the safety given that a low-carbohydrate diet and BA measurements may not be suitable for older individuals); (2) BMI of 21–40 kg m^{-2}; and (3) willingness to lose weight and manage obesity. The exclusion criteria included individuals who (1) had lost more than 10% of their body weight within the last three months, (2) were currently taking medication for the treatment of metabolic diseases, and (3) had experience with or were currently taking dietary supplements. The experimental procedure was explained in detail to all participants by the researchers, and written informed consent was obtained from all participants prior to the study. This study was approved by the institutional review board of Yonsei University (Yonsei IRB no. 7001988–201910-HR-674-05). This study followed the Consolidated Standards of Reporting Trials (CONSORT) reporting guideline [23].

The participants were randomly assigned to three parallel groups using a simple and stratified randomization method with a stratification factor of sex: the BA group, the BS (daily monitoring body weight) group, and a control group. Each group consisted of 15 participants with equal sex ratios. The participants flowchart is shown in figure 1. The randomization process was concealed from the research staff involved

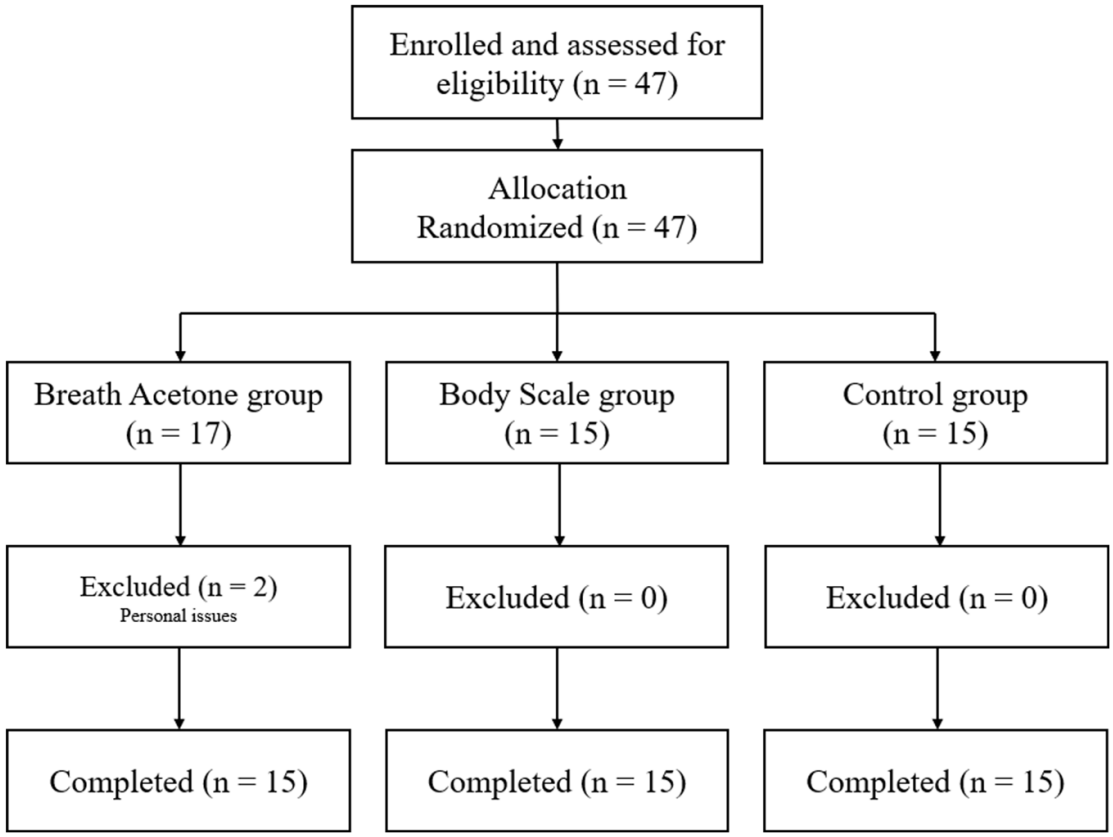

Figure 1. CONSORT diagram.

in the recruitment and assessment. The study participants were not blinded to the allocation of the study groups. Before enrolling in the study, all participants were informed about the study's objectives, and they were aware of the interventions conducted in the three different intervention groups. Participants visited the laboratory twice for study measurements, once at baseline and once post-intervention. Anthropometric and body composition measurements were taken on the first day. Additionally, on the first day of the visit, all participants attended an educational session on a low-carbohydrate diet prior to the interventions. The participants were then instructed to follow a low-carbohydrate diet for three weeks to increase body fat metabolism during the experiment and were advised to adhere to the diet throughout the intervention period. The diet intervention was not under direct supervision. Basal energy expenditure estimates were calculated using the Harris–Benedict equation [24], and participants' activity levels were adjusted to estimate their total daily energy expenditure [25]. The daily caloric intake was calculated by adjusting for a 15% reduction from the recommended daily caloric intake for calorie restriction. The participants were instructed to maintain a diet containing approximately 20% calories from carbohydrates, 60% from fat, and 20% from protein. After the intervention period, the participants visited the laboratory for the last time to undergo the same anthropometric measurements as on the first visit. The BA group visited the laboratory daily (every morning on weekdays) to measure their BA levels and received feedback on their body fat metabolism rate based on the dietary status of the previous day or on the day itself. Participants in the BA group were not instructed to adjust their dietary patterns based on the daily feedback they received; instead, they were simply provided with information about their body fat metabolism levels. Also, participants were not required to maintain a specific BA level during the intervention. The BS group visited the laboratory every morning on an empty stomach with an empty bladder to measure their weight and was provided with daily feedback on their weight records during the intervention period. In contrast, the control group did not receive feedback after their initial laboratory visit.

2.2. Measures

2.2.1. Body weight, body composition, visceral fat mass, and blood pressure

Participants' height and weight were measured using an electric extensometer (BDM 330, Biospace, Seoul, South Korea) to the nearest 0.1 kg and 0.1 cm, respectively. Additionally, the fat mass (kg), body fat percentage (%), skeletal muscle mass (kg), and visceral fat mass (cm^2) were measured using bioelectrical impedance analysis (Inbody 720, Biospace, Seoul, South Korea) [26]. BMI was calculated as weight (kg)

divided by height (m) squared. Blood pressure was measured using an electronic manometer (BPBio 320, Biospace, Seoul, South Korea), and the average of two measurements was recorded.

2.2.2. Breath acetone measurement

In this study, an integrated BA analyzer was employed, which comprised a sampling loop, packed column, three solenoid valves, a mini-sized pump, and a ZnO QDs-based sensor. The BA analyzer had dimensions measuring 8 cm in width, 13 cm in height, and 16 cm in depth [27]. The ZnO QDs-based sensor was tested for its performance, which confirmed its ability to selectively detect acetone up to 0.1 ppm in a mixed gas at 430 °C [27]. ZnO QDs were synthesized using a wet chemical method. Initially, a ZnO precursor solution was prepared by dissolving 1.975 g of Zn acetate (Zn(O2CCH3)2, Alfa Aesar) in 90 ml of N,N-dimethylformamide ((CH3)2NC(O)H, Duksan). The ZnO precursor solution was then introduced into a methanolic solution of tetramethylammonium hydroxide (N(CH3)4+(OH)−, with a ratio of methanol to tetramethylammonium hydroxide being 1:8), using a syringe pump for 1 h at 30 °C. After synthesis, the ZnO QDs were rinsed with acetone and dispersed in methanol. To create the ZnO QD-based sensor, the ZnO QD solution was dispersed onto an Al2O3 substrate and underwent heat treatment at 350 °C for 30 min to remove any residue. The microstructure of the ZnO QDs was examined using scanning electron microscopy (JEOL-7001F) and tunneling electron microscopy with energy-dispersive x-ray spectroscopy (JEM-F2000), which was also employed for the compositional analysis of the ZnO QDs [27, 28]. Creating acetone sensors using ZnO QDs involved applying QDs on an alumina substrate with Pt electrodes and heating elements. After drying at 90 °C and heat-treating at 350 °C for 30 min to remove organic compounds, the sensors were optimized for an operating temperature of 430 °C. The BA analyzer detected acetone concentrations from 0.1 to 50 ppm, achieved by directly injecting acetone into the analyzer for 10 s with a 1 ml sampling volume, using ambient air as the carrier gas at a flow rate of 30 sccm. For reference, at 430 °C, the ZnO QD sensor exhibited responses of 0.027, 0.054, 0.088, and 0.261 for acetone concentrations of 0.1, 0.5, 1, and 5 ppm, respectively. The sensor signal $\Delta(\log(R))$ represented the resistance change, with $\log(R)$max and $\log(R)$min indicating maximum and minimum resistances during acetone exposure [27]. To collect the BA samples, all participants fasted for 8 h before the breath analysis, and the last section of the participant's exhalation was captured in a Tedlar bag, which was then connected to the sampling loop inside the BA analyzer. The breath samples were stored in the Tedlar bag for no longer than 5 min. The initial 1L of exhalation was expelled into a standard plastic bag, while the final 50 ml of exhaled breath was collected for analysis. Only end-tidal breath was collected in 50 ml sample bag. Then, this bag was connected to the BA analyzer. BA was measured in a single breath without any deliberate preparation or excessive breathing. Participants refrained from smoking and alcohol consumption before the BA measurements. Once the sampling loop was filled with 1 ml of exhalation, it was passed through a packed column within 2 min. The separation of BA in the mixed gas occurred because of the difference in the polarities of the molecules and was based on the varying strengths of the interactions between the component gases and the highly polar stationary phase. Acetone, being polar, was separated from the column and detected by the change in the resistance of the ZnO QD-based sensor. The response of the sensor increased with increasing acetone concentration and exhibited a strong linear association with gas concentration ($R^2 = 0.992$), with a linear range spanning from 0 to 5 ppm [27]. For reference, the calibration and validation of the BA measurement were conducted using the BA analyzer employed in this study [27]. Lastly, there was no presence of relative humidities that could have influenced the results of the breath analysis [27].

2.3. Primary and secondary outcomes

The primary outcome was the change in fat mass. The secondary outcomes included changes in body weight, skeletal muscle mass, body fat percentage, visceral fat mass, and blood pressure.

2.4. Statistical analysis

Statistical analyses were based on the per-protocol principle and included all participants who completed both baseline and post-intervention data. Descriptive statistics, including frequency distribution and variability, were used to present the characteristics of the study participants. Differences in the study variables at baseline between the study groups were tested using a one-way analysis of variance (ANOVA). Differences in the study variables between pre- and post-intervention were tested using paired-samples *t*-tests or Wilcoxon signed-rank tests, as appropriate. Additionally, the difference in the average change in primary outcomes among the BA, BS, and control groups was examined using paired sample *t*-tests. In addition, the mean BA level of the BA group for three weeks of the intervention period was observed (figure 2) and categorized into three levels using a tertile split to determine whether changes in body weight and body composition were associated with BA levels. Differences in the changes in the study variables between the BA tertiles were examined using an ANOVA, and a Tukey post hoc test was conducted to examine any differences between the BA tertiles. Data were analyzed using SPSS version 25.0 (IBM, Armonk, NY, USA). A 2-tailed *P*-value of <0.05 was considered statistically significant.

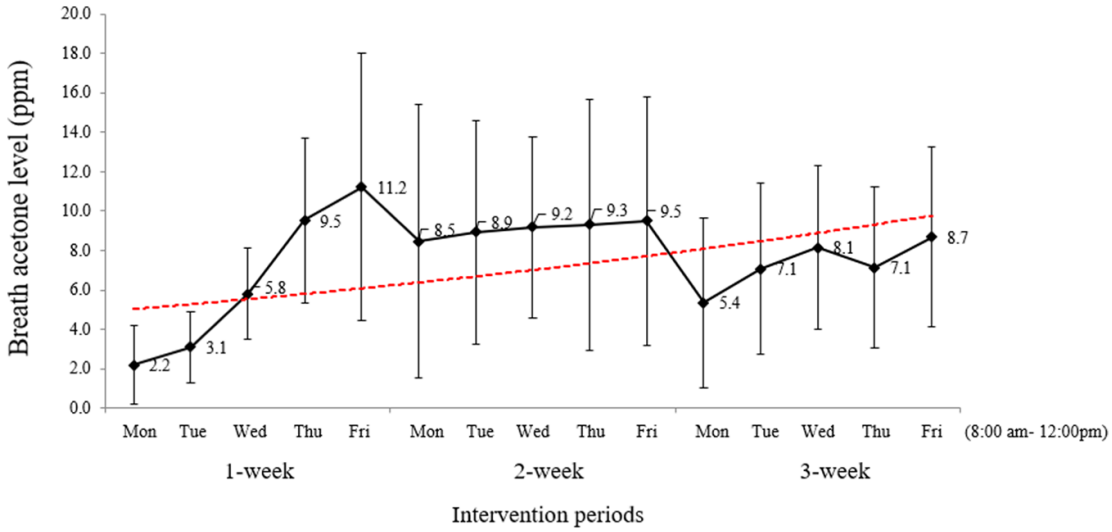

Figure 2. Mean (standard deviation) breath acetone levels in the breath acetone intervention group (n=15) across three weeks of intervention with no measurements during weekends. The red dotted line indicates an exponential trend.

Table 1. Baseline characteristics of the study participants by randomly assigned study groups.

Variables	Total ($n = 45$)	BA group ($n = 15$)	BS group ($n = 15$)	Controls ($n = 15$)	P-value
Female, n (%)	24 (53.3)	8 (53.3)	8 (53.3)	8 (53.3)	0.991
Age, years	27.8 ± 4.4	27.7 ± 4.5	27.8 ± 3.2	28.0 ± 5.6	0.968
Body weight, kg	67.8 ± 14.5	68.4 ± 13.3	67.0 ± 17.7	67.9 ± 13.9	0.444
Body mass index, kg m^{-2}	24.1 ± 3.4	24.5 ± 3.3	23.8 ± 3.8	23.8 ± 3.1	0.788
Body fat mass, kg	17.4 ± 5.6	19.0 ± 5.8	16.9 ± 4.6	16.2 ± 6.2	0.583
Percent body fat, %	25.9 ± 7.1	27.7 ± 5.9	25.6 ± 5.6	24.3 ± 9.2	0.889
Skeletal muscle mass, kg	28.1 ± 7.8	27.5 ± 6.2	28.0 ± 8.8	28.9 ± 8.6	0.381
Visceral fat mass, cm^2	72.1 ± 25.1	75.2 ± 23.6	76.2 ± 25.8	64.8 ± 25.9	0.240
Breath acetone, ppm	1.7 ± 1.8	2.1 ± 1.9	1.8 ± 2.2	1.2 ± 1.03	0.381
Systolic blood pressure, mmHg	116.9 ± 11.7	114.1 ± 10.9	116.5 ± 11.7	119.2 ± 11.97	0.346
Diastolic blood pressure, mmHg	78.2 ± 11.9	78.4 ± 14.3	79.8 ± 14.1	75.8 ± 7.4	0.707

Note: Data are n (%) or mean ± SD. P values, tests for differences by study group using ANOVA, as appropriate.
Abbreviations: BA: breath acetone; BS: body scale.

3. Results

Table 1 presents the baseline characteristics of the participants who completed the study protocols. Forty-seven participants were initially enrolled in the study; however, two dropped out because of personal issues. The mean age was 27.8 ± 4.4 years, with a BMI of 24.1 ± 3.4 kg m^{-2} and a baseline mean BA level of 1.7 ± 1.8 ppm. No significant differences were observed in any of the variables between the study groups.

Fat mass was significantly reduced in all three groups (all $P < 0.05$); however, the greatest reduction in fat mass was observed in the BA group compared to the BS (differences in changes in fat mass, −1.1 kg; 95% confidence intervals: −2.3, −0.2; $P = 0.040$) and control (differences in changes in fat mass, −1.3 kg; 95% confidence intervals: −2.1, −0.4; $P = 0.013$) groups (table 2).

Body weight and visceral fat mass significantly reduced in all three groups (table 2). The BA group showed significantly greater reductions in body weight and visceral fat mass than the BS and control groups (all $P < 0.05$). In addition, the percent body fat and skeletal muscle mass were significantly reduced in both BA and BS groups (all $P < 0.05$). However, no significant differences were found in changes in body fat percentage and skeletal muscle mass between the study groups. Diastolic blood pressure was significantly lower in the BA group ($P = 0.017$).

Figure 3 displays the changes in fat mass, body weight, and body composition after a three-week intervention across the tertiles of mean BA levels in the BA group ($n = 15$). Participants whose BA levels remained high (the 1st tertile) exhibited the greatest reduction in fat mass and visceral fat mass, followed by the 2nd and 3rd tertiles. Figure 1 depicts BA levels over the three-week study period in the BA group. The average BA level for the entire intervention period was 7.6 ppm, and the BA level was consistently increased over the 3 week intervention period.

Table 2. Changes in body fat mass and body composition between the study groups after three weeks of intervention.

Variables/Groups	Baseline	Post	Δ mean (95% CI)	*P*-value*	Difference in Δ mean between groups (95% CI)	*P*-value†
Body fat mass, kg						
BA group	19.0 ± 5.8	17.1 ± 5.2	**−1.9 (−2.6, −1.2)**	**<0.001**	—	—
BS group	16.9 ± 4.6	15.8 ± 5.5	**−0.8 (−1.9, −0.3)**	**0.008**	—	—
Controls	16.2 ± 6.2	15.6 ± 5.9	**−0.6 (−1.1, −0.2)**	**0.007**	—	—
Group comparisons					—	—
BA group vs. Controls	—	—	—	—	**−1.3 (−2.1, −0.4)**	**0.013**
BS group vs. Controls	—	—	—	—	−0.2 (−1.2, 0.9)	0.896
BA group vs. BS group	—	—	—	—	**−1.1 (−2.3, −0.2)**	**0.040**
Body weight, kg						
BA group	68.4 ± 13.3	65.8 ± 12.7	**−2.6 (−3.3, −1.9)**	**<0.001**	—	—
BS group	67.0 ± 17.7	65.0 ± 17.3	**−1.8 (−2.7, −0.8)**	**<0.001**	—	—
Controls	67.9 ± 13.9	67.0 ± 13.4	**−0.9 (−1.6, −0.3)**	**0.010**	—	—
Group comparisons						
BA group vs. Controls	—	—	—	—	**−1.7 (−2.9, −0.4)**	**0.006**
BS group vs. Controls	—	—	—	—	−1.2 (−2.1, 0.4)	0.212
BA group vs. BS group	—	—	—	—	−0.8 (−2.0, 0.4)	0.264
Percent body fat, %						
BA group	27.7 ± 5.9	25.9 ± 5.9	**−1.8 (−2.6, −0.9)**	**<0.001**	—	—
BS group	25.6 ± 5.6	24.3 ± 5.9	**−1.1 (−2.1, −0.2)**	**0.021**	—	—
Controls	24.3 ± 9.2	23.8 ± 9.3	−0.6 (−1.1, 0.0)	0.050	—	—
Group comparisons						
BA group vs. Controls	—	—	—	—	−1.2 (−2.4, 0.0)	0.058
BS group vs. Controls	—	—	—	—	−0.2 (−1.5, 1.0)	0.885
BA group vs. BS group	—	—	—	—	−1.0 (−2.2, 0.3)	0.154
Visceral fat mass, cm^2						
BA group	75.2 ± 23.6	66.8 ± 22.3	**−8.3 (−10.6, −6.1)**	**0.001**	—	—
BS group	76.2 ± 25.8	71.4 ± 29.2	**−4.7 (−8.0, −1.5)**	**0.008**	—	—
Controls	64.8 ± 25.9	61.6 ± 24.8	**−3.3 (−5.0, −1.5)**	**0.001**	—	—
Group comparisons						
BA group vs. Controls	—	—	—	—	**−5.0 (−9.1, −1.0)**	**0.011**
BS group vs. Controls	—	—	—	—	−1.4 (−5.5, 2.6)	0.658
BA group vs. BS group	—	—	—	—	−3.6 (−7.6, 0.4)	0.087

(Continued.)

Table 2. (Continued.)

Variables/Groups	Baseline	Post	Δ mean (95% CI)	*P*-value*	Difference in Δ mean between groups (95% CI)	*P*-value†
Skeletal muscle mass, kg						
BA group	27.5 ± 6.2	27.1 ± 6.2	**−0.3 (−0.6, −0.1)**	**0.008**	—	—
BS group	28.0 ± 8.8	27.4 ± 8.4	**−0.5 (−0.9, −0.1)**	**0.011**	—	—
Controls	28.9 ± 8.6	28.7 ± 8.4	−0.1 (−0.5, −0.2)	0.367	—	—
Group comparisons						
BA group vs. Controls	—	—	—	—	−0.2 (−0.7, 0.3)	0.669
BS group vs. Controls	—	—	—	—	−0.4 (−0.9, 0.1)	0.200
BA group vs. BS group	—	—	—	—	0.2 (−0.3, 0.7)	0.650
Systolic blood pressure, mmHg						
BA group	114.1 ± 10.9	108.0 ± 12.6	−6.1 (−12.1, 0.0)	0.050	—	—
BS group	116.5 ± 11.7	110.6 ± 20.8	−6.0 (−14.6, 2.6)	0.727	—	—
Controls	119.2 ± 12.0	114.2 ± 9.4	−5.0 (−11.2, 1.2)	0.124	—	—
Group comparisons						
BA group vs. Controls	—	—	—	—	7.6 (−17.3, 32.6)	0.740
BS group vs. Controls	—	—	—	—	0.4 (−24.6, 25.4)	0.999
BA group vs. BS group	—	—	—	—	7.2 (−17.7, 32.2)	0.763
Diastolic blood pressure, mmHg						
BA group	78.4 ± 14.3	71.5 ± 8.1	**−7.0 (−13.2, −0.7)**	**0.017**	—	—
BS group	79.8 ± 14.1	74.5 ± 9.7	−5.2 (−15.8, 5.4)	0.572	—	—
Controls	75.8 ± 7.4	74.5 ± 4.6	−1.3 (−5.1, 2.5)	0.432	—	—
Group comparisons						
BA group vs. Controls	—	—	—	—	−0.2 (−18.9, 18.6)	0.999
BS group vs. Controls	—	—	—	—	−3.6 (−22.4, 15.1)	0.885
BA group vs. BS group	—	—	—	—	3.5 (−15.3, 22.2)	0.895

Note: Δ mean indicates postintervention baseline values. Bold font indicates statistical significance. **P*-value tests for a difference between baseline and post-intervention using either paired samples *t*-tests or Wilcoxon signed-rank test, as appropriate. †*P*-value tests for a difference in Δ mean between study groups using paired samples t-tests.

Abbreviations: BA: breath acetone; BS: body scale.

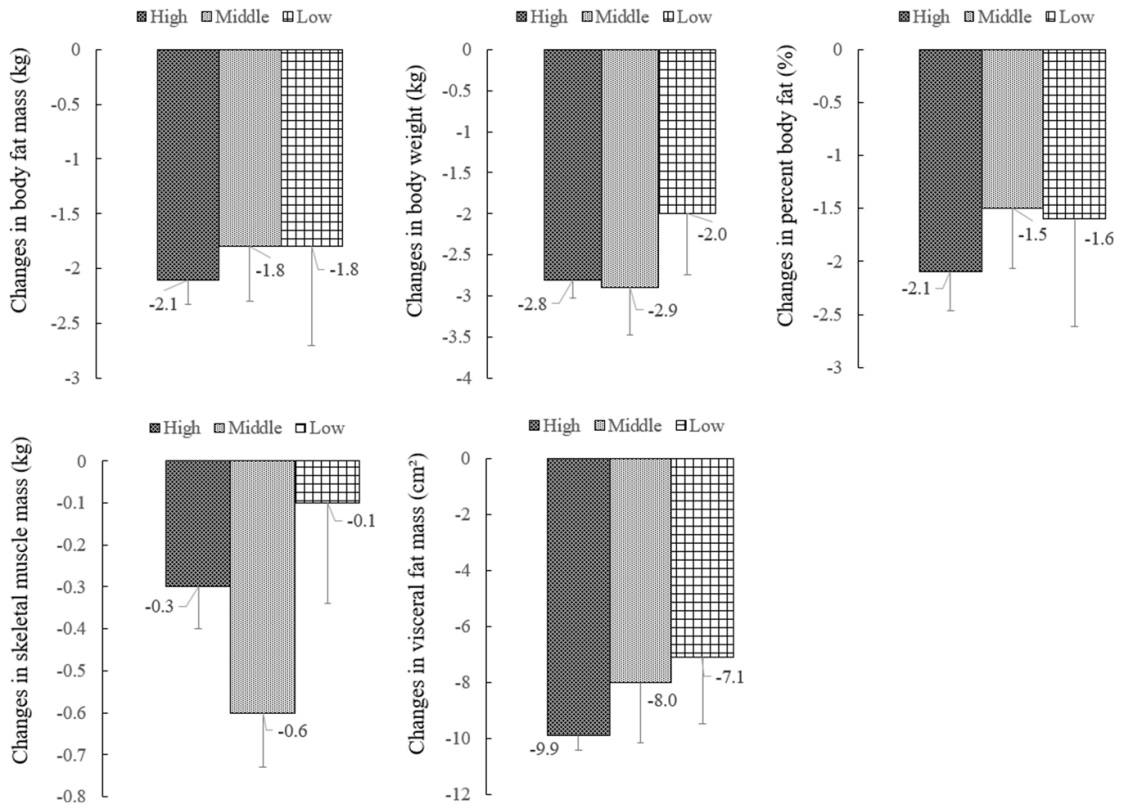

Figure 3. Changes in body fat mass, body weight, percent body fat, skeletal muscle mass, and visceral fat mass after three weeks of intervention across tertiles of breath acetone levels in the breath acetone intervention group ($n = 15$).
Note: High ($n = 5$) represents the highest tertile of breath acetone level, middle ($n = 5$) represents the middle tertile of breath acetone level, and low ($n = 5$) represents the lowest tertile of breath acetone level. Tertile of mean breath acetone level cutoff points (ppm): $4.6 \leqslant$ low $\leqslant 5.5$, $6.2 \leqslant$ middle $\leqslant 8.5$, $8.7 \leqslant$ high $\leqslant 12.2$. *None of the study variables were statistically different between tertiles of levels in breath acetone.*

4. Discussion

Although the potential effectiveness of using BA measurements in reducing body fat mass has been suggested [8, 13, 29], no randomized clinical trial has assessed the efficacy of BA measurements in reducing fat mass. The current study revealed that daily measurement of BA and the subsequent high compliance with the low-carbohydrate diet may be more effective than daily measurement of body weight in reducing fat mass in a low-carbohydrate diet. We assumed that daily BA measurements could have motivated participants to adhere more closely to the low-carbohydrate diet. The study displayed a significant reduction in the body weight of participants in both the BA and BS groups compared with the control group. However, there were no significant differences in body weight between the BA and BS groups. These results indicate that monitoring BA levels may improve adherence to low-carbohydrate diet interventions, resulting in a greater reduction in fat mass.

Regarding the BA monitoring intervention, providing specific and precise information about the magnitude of ketosis and the rate of fat metabolism, such as the quantity of body fat decomposition per unit of time (g/h), was effective in enhancing adherence to a low-carbohydrate diet. Furthermore, the BA monitor provided additional suggestions for adjusting dietary components in response to real-time BA levels. We observed that the BA level in the BA intervention group was consistently increased throughout the intervention period. A novel technology that measures BA levels and delivers real-time digital outcomes may serve as a more effective and engaging approach, as growing evidence has revealed the superiority of digital technology-driven interventions over traditional methods for promoting successful adherence and improving research outcomes [30, 31]. The implementation of digital interventions, including programs and devices that utilize digital technology, has great potential to improve the efficiency of healthcare delivery and population health outcomes [32]. Our findings also demonstrated that using an ambient BA monitor can effectively facilitate lifestyle modifications and improve obesity management [20, 32]. However, self-weighing or monitoring one's body weight is a common and routine activity in daily life that may not be sufficient to promote lifestyle changes and ensure strong adherence to dietary intervention. Frequent monitoring of body weight may reduce its

motivational impact, causing participants to become desensitized to the intervention [33].

Our results are consistent with previous findings demonstrating that maintaining high BA levels results in a greater reduction in fat mass. Prior research has suggested that maintaining a BA level of 2 ppm can result in a reduction of up to 227 g/week in fat mass, while an increase to 8 ppm could correspond to a reduction of 1.2 kg/week in fat mass (note that basal levels of ketosis and BA typically range from 1 to 2 ppm when consuming a standard diet) [8, 34]. Throughout the study period, we consistently observed high levels of acetone in the BA group, with most of the study visits showing acetone levels greater than 8.0 ppm, accounting for over 50% of the measures taken. Consequently, the BA group experienced a 1.3 kg reduction (corresponding to approximately 433 g/week) in fat mass, and this result was similar to the aforementioned findings from the literature.

In addition, body weight was significantly reduced within both BA and BS groups after the intervention period. However, there was no significant difference in body weight reduction between the two groups. Daily monitoring of body weight appeared to encourage the participants to lose weight by reducing their caloric intake and losing fat mass and fat-free mass. In contrast, daily monitoring of BA levels could have motivated participants to consume fewer carbohydrates but did not necessarily lead to a reduction in calorie intake. Our results suggest that monitoring BA levels was effective in reducing fat mass, whereas both monitoring body weight and BA levels were effective in promoting weight loss. Nevertheless, additional studies are warranted to confirm the applicability and validity of our findings across different settings for implementing BA monitoring protocols in obesity management research.

In particular, all our study groups experienced significant reductions in visceral fat mass; however, only the BA monitoring intervention resulted in a greater reduction in visceral fat mass compared with the control group. Moreover, none of the interventions had a significant effect on the change in blood pressure, except for a significant reduction in diastolic blood pressure after the BA monitoring intervention. A systematic review and meta-analysis by Santos *et al* [35] has revealed that a low-carbohydrate diet is effective in reducing both abdominal circumference (as a proxy measure of visceral fat) and blood pressure [35]. Our findings suggest that, similar to those of a review study [35], a low-carbohydrate diet, especially supplemented with daily BA measurements, may be effective in reducing visceral fat mass. However, the effects of daily BA monitoring and weighing interventions on visceral fat mass reduction did not differ significantly. The relatively short study period and lower BMI of our participants in comparison to those in the review and meta-analysis [35] might help to explain the lack of significant changes in blood pressure. The study periods included in the review by Santos *et al* [35] ranged from a minimum of six months to 24 or more months, and the mean BMI in the included studies was at least 29.1–42.9 kg m^{-2}. In contrast, our study had a shorter intervention period of three weeks and a lower mean BMI of 24.1 kg m^{-2} among participants. Visceral fat and blood pressure are important cardiometabolic risk factors in obesity prevention and management plans because they are closely associated with chronic diseases such as cardiovascular diseases, hypertensioMn, and hyperglycemia [35–37]. Therefore, future studies should examine the effectiveness of real-time BA monitoring in reducing visceral fat mass and improving blood pressure to prevent cardiometabolic disorders in different populations and research settings.

Our study had several limitations. First, the low-carbohydrate diet intervention was not fully supervised or monitored during the study period; therefore, the adherence rate could not be evaluated. In addition, although there were no differences in body weight and composition at baseline between the study groups, residual confounding factors may have been present because of individual variations in basal metabolism rate or energy expenditure from physical activity. A clear next step in future research is to compare the effects of a BA monitoring intervention with a weighing intervention when the energy balance from diet and physical activity is well controlled. Additionally, the short intervention period or lack of follow-up studies may limit the generalizability of our findings; however, extending the study period could lead to high attrition rates because of the difficulty in maintaining a long-term low-carbohydrate diet [38]. The compliance rate with the BA monitoring intervention in our study was 88.2%. Lastly, our study findings cannot be generalized to other racial or age groups and overweight or obese individuals.

5. Conclusions

Providing daily BA levels using a portable acetone monitor for three weeks and the subsequent high compliance with the low-carbohydrate diet may be more effective in reducing body fat mass than daily monitoring of body weight in intervention and control conditions when all participants follow a low-carbohydrate diet. The study findings suggest a novel health implication: daily monitoring of BA levels using fast, cost-efficient, and portable diagnostic technology could be an effective and sustainable lifestyle intervention for obesity prevention and management. To advance our understanding and application of BA monitoring systems to promote lifestyle modifications, future research must replicate our study in more rigorous and controlled interventions with diverse populations. Therefore, efforts should be made to develop more advanced and easily accessible BA-monitoring technologies that can be incorporated

into daily life to support the implementation of lifestyle modification strategies.

Data availability statements

The data cannot be made publicly available upon publication because no suitable repository exists for hosting data in this field of study. The data that support the findings of this study are available upon reasonable request from the authors.

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