Original Article
CLINICAL TRIALS AND INVESTIGATIONS

Obesity

Characterizing the Pattern of Weight Loss and Regain in Adults Enrolled in a 12-Week Internet-Based Weight Management Program

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Objective: Although the trajectory of weight change during and/or after behavioral weight management interventions is believed to include a period of weight loss followed by maintenance and later regain, the sparse data produced by existing study designs (conducting assessments at 3- to 6-month intervals) have limited investigation into the precise pattern.

Methods: Seventy-five adults were asked to self-weigh daily via "smart" scales during a 12-week, Internet-based weight loss program and for an additional 9 months with no further intervention. Longitudinal change-point mixed-effect models were used to characterize overall weight change patterns and identify when individuals moved from weight loss to maintenance/regain.

Results: Analyses suggested a three-phase model. During the first phase, participants lost weight at a (mean $\pm$ SE) rate of -0.46 ± 0.04 kg/wk; after 77.66 ± 3.96 days, they transitioned to regain (0.07 ± 0.02 kg/wk). The next transition occurred at 222.55 ± 7.23 days, after which the rate of regain decreased slightly (0.06 ± 0.02 kg/wk). Exploratory analyses identified baseline/demographic factors predicting the timing of transition points and slope of weight change within phases.

Conclusions: In contrast to the hypothesized trajectory, results demonstrated that participants transitioned immediately from weight loss to regain (with no "maintenance" period) and later to a slower rate of regain. Future studies should investigate whether extended-care programs change or merely delay this pattern.

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Introduction

Behavioral weight management interventions consistently produce weight losses of 7% to 10% of initial body weight during initial treatment (typically 4-6 months) in adults with overweight and obesity (1); however, successful weight loss maintenance following the end of intervention remains a challenge. Although some individuals are able to successfully maintain their weight losses, data collected at longer-term follow-up visits have demonstrated that participants, on average, tend to regain one-third to one-half of weight lost within a year of the end of treatment (1,2).

Although the general trend for weight regain after the end of weight management treatment has been well documented (2,3), investigation into the precise timing of weight regain (and the individual variability in this timing) has been challenging, given that most trials utilize study designs that space follow-up assessments at 3- to 6-month intervals. Thus, although the individual trajectory of weight change during and/or after behavioral weight management interventions is generally believed to include a period of weight loss followed by a period of maintenance and then a later shift to regain, the sparse data produced by existing study designs have prevented further investigation into this pattern.

Recent technological advances, such as the development of "smart" scales that can be used in participants' homes and send weight data back to research servers via wireless or cellular networks, have made the collection of more frequent weight data possible. These scales have been demonstrated to have good concordance compared to "official" assessment weights measured in person (4); thus, coupled with study protocols that ask participants to weigh themselves weekly or daily, data from these scales can allow researchers to investigate the time course of weight loss and regain with much more precision.

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The current study used data collected from these smart scales during a 12-week, internet-based weight management program followed by a 9-month "maintenance" period, during which no additional intervention was provided. Participants were asked to weigh themselves daily during the entire year of observation, and we hypothesized that these data would demonstrate a three-phase pattern of weight change, including a phase of initial weight loss, a phase of maintenance (or a plateau in weight loss), and then regain. As exploratory aims, we proposed to investigate the association between the rate of weight change during these phases and the timing of transition points at which an individual moved from one phase to the next (e.g., "Do participants who lose weight at a faster rate during the first phase transition to the next phase sooner than those with a slower rate of initial weight loss?"), the association between the rate of weight change during phase 1 and subsequent phases (e.g., "Do participants who lose weight at a faster rate initially also regain weight faster during later phases?"), and the association between the rate of weight change during phase 1 and overall weight loss during the 1-year study period (replicating existing research that has demonstrated a strong association between initial weight loss and long-term weight loss outcomes (5,6)). Finally, we proposed to investigate whether any baseline or demographic characteristics were associated with the timing of the transition between phases or the rate of weight change during these phases.

Methods

Participants

The current study was conceptualized as an observational trial of weight loss, maintenance, and regain. Participants were 75 employees or dependents of employees of a large health care corporation in Providence, Rhode Island, with ages between 18 and 70 years and BMI at baseline equal to or greater than 25 kg/m^2 (considered as within the range of "overweight" or "obesity") (7). Participants had previously enrolled in a workplace health care reward program, had expressed interest in weight loss, and were contacted through emails, texts, and advertisements on the work site intranet. If interested, participants were prescreened via an online questionnaire and initially eligible individuals were scheduled to attend an in-person orientation visit in which they received more information about the study, provided written informed consent, and completed final screening measures. Approval for this study was obtained from The Miriam Hospital Institutional Review Board. Participants were excluded if their body weight was $>$ 150 kg (a limitation of the in-home smart scales that were used) or if they reported medical conditions that would contraindicate changes in eating and/or physical activity for weight loss (e.g., uncontrolled hypertension or diabetes, treatment for cancer, recent history of coronary heart disease, self-report of an eating disorder, inability to walk at least two blocks without stopping), participation in another weight loss study at our center in the past 2 years, weight loss of $\geq$ 4.5 kg in the month prior to enrollment, or any other factors that would make it unlikely that they would complete the study (e.g., plans to move out of the area during the study period, substance abuse, terminal illness, severe psychiatric conditions, dementia).

Intervention

A complete description of the 12-week, internet-based behavioral weight management program that was provided to participants has been published previously (8). Briefly, as part of this program, participants attended a one-time, in-person group visit basic weight management education and tailored calorie, dietary fat, and physical activity goals. At this visit, participants were further taught how to self-monitor eating and activity habits and were provided with an in-home smart scale that sent weights directly back to our research servers. Participants were taught how to use these scales and were instructed to weigh themselves once each day. Participants were then asked to log into the study website each week for 12 weeks to receive interactive, multimedia-based weight management lessons (12-15 minutes each) based on content adapted from the Diabetes Prevention Program (9) and the Action for Health in Diabetes trial (10). Participants also self-reported their self-monitoring data weekly during the 12-week intervention and received automated, tailored feedback based on these data. After the end of the 12-week program, participants were asked to continue to log into the study website weekly to provide summaries of their self-monitoring habits and to answer brief questionnaires; however, they no longer had access to the intervention content and were no longer provided with the automated, tailored feedback. As the parent study was designed to assess factors associated with weight maintenance and weight regain, participants were given small financial incentives both during the 12-week intervention and during the 9-month no-contact observation period for providing self-monitoring data (note: the self-monitoring itself was not incentivized, as participants could receive the incentive for reporting that they did not self-monitor). Incentives ranged from \$1 to \$10 per week, were delivered in a pattern unknown to participants, and averaged \$3.50 per week (participants could earn up to a total of \$156 over the course of the year). Further, participants were allowed to keep the smart scales after the end of the study; however, the data link to our center was extinguished.

Measures

At the initial in-person intervention visit, participants were provided with a BodyTrace smart scale (BodyTrace Inc., New York, New York) to use at home and were asked to weigh themselves once each day, first thing in the morning, after voiding but prior to having anything to eat or drink. These scales transmitted weight data directly to a research server and stored values in pounds (we converted pounds to kilograms at 1 lb = 0.45359237 kg), with stated accuracy to 0.1 kg (11). Demographic information was collected at baseline using a self-report questionnaire.

Statistical analyses

Analyses were conducted using R version 3.1.3 (R Foundation for Statistical Computing, Vienna, Austria) and SAS version 9.4 for Windows (SAS Institute, Cary, North Carolina). Weight data were prepared for analyses by removal of duplicate entries (i.e., more than one weight measurement recorded in a single day) and outliers (frequently indicative of another person in the household using the scale). To identify outliers, generalized additive models of weight over time were fit by individual, and points at which residuals from this model were greater than 2.27 kg above predicted values were visually inspected and removed if not consistent with the weights measured during the prior two and following two observations. If multiple weights were recorded on a single day, the first (earliest) nonoutlier weight was retained while the others were removed.

Longitudinal change-point mixed-effect models were used to characterize weight change over time for each participant, using all observed weights. Although we hypothesized that a model with two change points (representing three distinct phases of weight change, maintenance, and loss) would provide the best fit, we used the Akaike Information Criterion to evaluate whether a two-phase (one change point) model provided a better fit. Between change points, changes in body weight were characterized as a linear function of time, and it was assumed that body weight would be a continuous function of time (that is, the "phases" within an individual would be connected together). For each individual (i), we let τ_{i1}, τ_{i2} denote the two change points that delimited the three phases, and the line segment in each phase was formulated as a linear function of time t with intercept and slope of $a_{ik} + b_{ik}t$. With body weight observed at a set of time points $\{t_{ij}\}_{j=1}^{n_i}$ and with n_i being the total number of observed weights for the i-th individual, the observed body weight at time t_{ij} was modeled by using

$$\begin{aligned} y_{ij} = & (a_{i1}+b_{i1}t_{ij})I(t_{ij} < \tau_{i1}) \\ & +(a_{i2}+b_{i2}t_{ij})I(\tau_{i1} \le t_{ij} < \tau_{i2}) \\ & +(a_{i3}+b_{i3}t_{ij})I(\tau_{i2} \le t_{ij})+\epsilon_{ij} \end{aligned}$$

with continuity constraints as follows:

$$a_{i1}+b_{i1}\tau_{i1}=a_{i2}+b_{i2}\tau_{i1}$$

$$a_{i2}+b_{i2}\tau_{i2}=a_{i3}+b_{i3}\tau_{i2}$$

For each individual, parameters τ_{i1}, τ_{i2}, b_{i1}, b_{i2}, and b_{i3} were modeled by using a random-effect model, assuming that that τ_{i1}, τ_{i2}, b_{i1}, b_{i2}, and b_{i3} were independent observations from the distribution $N(\mu, \sigma^2)$:

$$\begin{aligned} \tau_{i1} &= T_1+u_{i1}, u_{i1} \sim N(0,\sigma^2_{T_1}) \\ \tau_{i2} &= T_2+u_{i2}, u_{i1} \sim N(0,\sigma^2_{T_2}) \\ b_{i1} &= B_1+v_{i1}, v_{i1} \sim N(0,\sigma^2_{B_1}) \\ b_{i2} &= B_2+v_{i2}, v_{i2} \sim N(0,\sigma^2_{B_2}) \\ b_{i3} &= B_3+v_{i3}, v_{i3} \sim N(0,\sigma^2_{B_3}) \end{aligned}$$

For any individuals who demonstrated only two phases, we assumed that parameter estimates also came from the above distributions, with τ_{i2} and b_{i3} considered missing.

Linear regressions were used to assess the association between the timing of the first change point (τ_1) and the timing of the second change point (τ_2), the association between the slope (rate of weight change) between the change points and the timing of the change points, the association between the rate of weight loss in phase 1 (b_1) and subsequent phases (b_2 and b_3), and the association between the rate of initial weight loss (b_1) and the overall weight change from baseline to 1 year. Finally, we used stepwise linear regression models to conduct exploratory analyses investigating whether any baseline and demographic factors (baseline BMI, age, gender, income, education level, and marital status) were associated with the change points and slopes of weight change identified in the main model.

Results

Of the 75 participants initially enrolled in the study, 70 were included in the final model (data from 5 participants were removed because of missing data that prevented model fit). The 5 participants removed from analyses all had less than 100 days of weight data (mean ± SD of 40.60 ± 29.13 days, range = 8 to 79 days). Demographic and baseline characteristics of included and excluded participants are provided in Table 1; there were no differences between participants who were included or excluded from the current analyses in terms of age, baseline weight, BMI, gender, race/ethnicity, marital status, household income, or education.

Adherence to the self-weighing protocol was excellent; after the removal of duplicate and outlier weight values, included participants weighed themselves on an average (mean ± SD) of 272.20 ± 64.09 days, or 74.58 ± 17.56% of potential days (median = 287 days or 78.6% of days; range = 105 to 365 days, maximum possible days = 365).

The data fit a three-phase model for 65 of the 70 participants (Figure 1) and a two-phase model for 5 participants. Participants lost, on average (mean ± SE), −0.46 ± 0.04 kg/wk during the initial phase. For all participants, the first phase lasted an average of 77.66 ± 3.96 days (at which time the first change point occurred). During the second phase, participants began regaining an average of 0.07 ± 0.02 kg/wk. The second change point occurred at 222.55 ± 7.23 days, after which the slope of weight regain decreased slightly to 0.06 ± 0.02 kg/wk.

For the 65 participants with a three-phase model, there was no association between the initial rate of weight change during phase 1 and the timing of the first change point ($P = 0.529$). In addition, there was no association between the initial rate of weight loss during phase 1 and the rate of weight regain in phase 2 ($P = 0.146$) or phase 3 ($P = 0.224$), and the rate of regain in phase 2 was also not significantly associated with the rate of regain in phase 3 ($P = 0.107$). There was, however, an association between the rate of initial weight loss and overall weight loss ($F[1,64] = 97.88$, $\beta = 0.28$, $R^2 = 0.61$, $P < 0.001$), such that participants who had the fastest rate of weight loss during phase 1 had the largest weight losses overall between baseline and 1 year. Likewise, we found no significant association between the timing of the first change point and the slope of weight regain during phase 2 (i.e., participants who began regaining sooner did not necessarily begin regaining faster; $P = 0.991$) or between the timing of the first change point and the length of phase 2 (the time between the first change point and the second change point; $P = 0.155$). A stepwise regression identified several baseline and demographic factors associated with model parameters (i.e., the model-identified change points and slopes of weight change between the change points; Table 2). For example, having a higher baseline BMI was associated with a faster rate of initial weight loss and a later transition to the weight regain phase from the weight loss phase but was also associated with a later transition to phase 3 (the phase with a slower rate of regain) from phase 2 (the phase of more rapid regain, immediately after weight loss) and a faster rate of regain during phase 3. Men lost weight at a faster rate than women during phase 1 but also regained weight at a faster rate during phase 2. Compared to younger participants, older participants regained weight at a slower rate during phase 2 and, furthermore, transitioned from phase 2 (the phase of more rapid regain) to phase 3 (the phase of less rapid regain) sooner.

Discussion

In contrast to the expected pattern of weight loss followed by a period of maintenance and then a later shift to weight regain, the

TABLE 1 Baseline and demographic characteristics

	Included participants ($n = 70$)		Excluded participants ($n = 5$)		
	M	SD	M	SD	*P*
Age	50.84	10.31	49.60	12.50	0.442
Weight (kg)	85.64	16.63	83.32	18.87	0.566
BMI (kg/m^2)	30.86	4.57	31.00	3.84	0.822
	n	%	*n*	%	
Gender					0.639
Female	49	70.0	3	60.0	
Male	21	30.0	2	40.0	
Race/ethnicity					0.593
African American	4	5.7	0	0.0	
Asian	1	1.4	0	0.0	
Caucasian	59	84.3	4	80.0	
Hispanic	2	2.9	0	0.0	
Other/multiple	4	5.7	1	20.0	
Marital status					0.179
Single	4	5.7	1	20.0	
Married or living with a partner	57	81.4	4	80.0	
Separated/divorced/widowed	9	12.9	0	0.0	
Household income (dollars)					0.454
25,000-50,000	7	10.0	0	0.0	
50,001-75,000	13	18.6	3	60.0	
75,001-100,000	17	24.3	1	20.0	
100,001-125,000	10	14.3	0	0.0	
125,000+	21	30.0	1	20.0	
Not reported	2	2.9	0	0.0	
Education					0.061
High school or less	5	7.1	1	20.0	
Vocational training	2	2.9	0	0.0	
Some college	11	15.7	3	60.0	
College or university degree	33	47.1	1	20.0	
Graduate degree	19	27.1	0	0.0	

M, mean.

results of this study demonstrated that the pattern of weight change for adults with obesity who took part in a 12-week, internet-based behavioral weight loss program included a period of weight loss followed by a period of weight regain, which later transitioned to a slower rate of regain. Although the shape of this trajectory matches the "check mark" pattern of group mean change observed during follow-up visits (spaced at 3-6 months) of many existing behavioral weight management trials (2,3), it was previously unknown whether individual trajectories followed this pattern in the times between the formal assessment visits. Furthermore, it is not consistent with the mathematical models and simulations of weight loss and regain developed by Hall and colleagues (12), which suggest a pattern of weight loss, a plateau, and eventual regain. These models and simulations, however, were developed initially to accommodate the metabolic adaptation that occurs as an individual loses weight, which the authors noted would not occur for most individuals until several years after the initiation of weight loss. Further, Hall et al. (12) noted that the weight regain demonstrated in behavioral weight management programs (typically observed far before this time frame, around 6-9 months after the initiation of treatment) is likely due to nonadherence to the changes in dietary intake and physical activity that produced the initial weight loss. Although we did not investigate changes in dietary intake and physical activity following treatment in the current study, decreases in adherence to these behavioral changes are a likely driver of the early transition to weight regain observed in the current results.

It is important to note that the transition from weight loss to regain occurred earlier in this study (at 11 weeks) compared to the 6 to 9 months documented in other behavioral weight management trials (3). This may have been a function of the length of initial treatment; our initial treatment was conducted over 12 weeks, whereas many

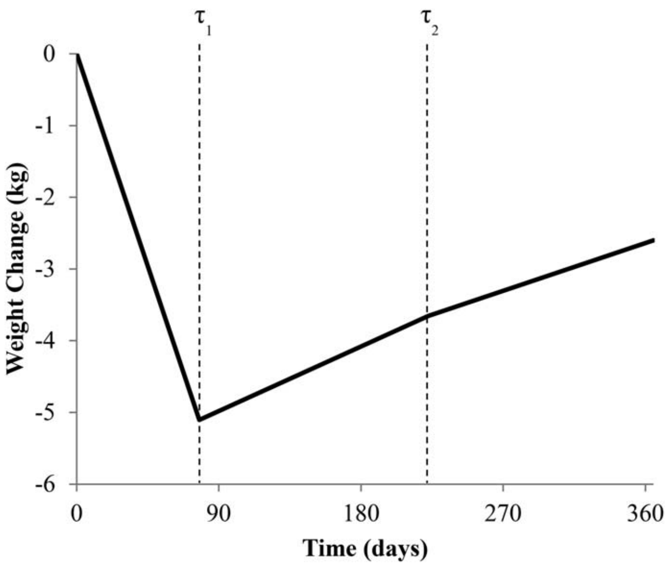

Figure 1 Modeled change in weight over time, across all participants with a three-phase model ($n = 65$).

existing trials have provided intervention (including initial intervention and, frequently, "extended-care" maintenance sessions) for 6 to 12 months. Alternatively, it may be due to the fact that most trials have included assessments at 6 months, possibly missing this first inflection point. Future research should investigate whether this same pattern (a transition from weight loss to weight regain, without an intermediate plateau or maintenance period) exists after longer (6- to 12-month) weight management interventions and whether, given the increase in conceptualization of obesity as a chronic condition necessitating ongoing care (13,14), this pattern exists when participants are provided with extended-care or maintenance programs after the cessation of the initial intervention.

Other key findings of the current study include the replication of the association found between initial weight loss success and long-term weight loss outcomes (5,6), as we found that the rate of weight loss during the first phase was significantly associated with overall weight loss during the course of the intervention and follow-up period (a total of 1 year). Further, the rate of weight loss during this initial phase averaged around a pound per week, which is consistent with the clinical goals of the intervention and other existing intervention protocols (9,10). Finally, our exploratory analyses identified several baseline and demographic factors (e.g., baseline BMI, gender, age) that predicted both the timing of the transition points between phases and the slope of weight change within each phase. These findings are a starting point for the identification of factors that may, with further research, serve as treatment-tailoring variables. As increasing access to mobile technology provides the potential to deliver intervention on an individually tailored level when and where it is needed (15), an important next step will be to identify what factors (especially those that are modifiable) more proximally predict the transition point from weight loss to weight regain.

Despite these findings, the current study had several important limitations. First, as we intended to study and observe the course of weight maintenance and regain, we did not provide an extended-care intervention after the end of initial treatment, despite evidence that providing additional contact after the end of treatment can improve maintenance and long-term weight loss outcomes (14). Future studies should investigate weight change trajectories during and after the provision of extended-care programs and investigate whether these interventions are able to change or merely delay the pattern of weight loss and regain observed in our data. Second, the

TABLE 2 Association between demographic and baseline characteristics and the timing of transition points and the slope of weight change between these transition points

	β	*t*	*P*
Factors associated with greater initial weight loss (b_1)			
Baseline BMI (higher BMI = faster rate of weight loss)	−0.026	−4.26	< 0.001
Gender (male = faster rate of weight loss)	−0.228	−3.69	< 0.001
Income (higher income = faster rate of weight loss)	−0.056	−2.75	0.008
Factors associated with later transition from phase 1 to phase 2 (τ_1)			
Baseline BMI (higher BMI = later transition)	1.647	2.05	0.045
Income (lower income = later transition)	−7.838	−2.70	0.009
Factors associated with slower weight regain during phase 2 (b_2)			
Baseline age (older adults = slower rate of regain)	0.003	2.18	0.034
Gender (female = slower rate of regain)	0.088	2.24	0.029
Marital status (married/living with a partner = slower rate of regain)	0.092	2.14	0.037
Factors associated with transition from phase 2 to phase 3 (τ_2)			
Baseline BMI (lower BMI = later transition)	3.231	2.18	0.034
Baseline age (younger adults = later transition)	−2.213	−3.04	0.004
Race/ethnicity (Non-Hispanic White participants = later transition)	44.213	2.24	0.290
Factors associated with slower weight regain during phase 3 (b_3)			
Baseline BMI (lower BMI = slower rate of regain)	0.012	2.49	0.016

current study utilized an internet-based behavioral intervention, and although several studies have documented the efficacy of the intervention program used for weight loss (16-18), few have investigated the long-term impact of these programs or whether weight regain varies compared to gold-standard, face-to-face, group-based behavioral interventions (19). Thus, these results should be replicated in other behavioral interventions and across treatment-delivery modalities. Finally, the sample predominately consisted of non-Hispanic White women, which limits generalizability of the results to the broad population.

Despite these limitations, study strengths included a prospective study design (this study was designed specifically to evaluate the pattern of weight loss, maintenance, and regain), excellent adherence to the daily self-weighing protocol (especially given the lack of reminders or intervention contact during the 9-month maintenance period after the end of the 12-week, internet-based behavioral weight management program), and the collection of an entire year of objective weight data using in-home smart scales that sent weights directly back to our research center (compared to the reliance on self-reported data). Although most behavioral weight management interventions have conducted follow-up assessments at 3- to 6-month intervals, the current study represents the first attempt to investigate the pattern of weight loss and weight regain on a more proximal level, by using daily objective weights to characterize this pattern over time.

Conclusion

The results from the current study challenge our understanding of the shape of the trajectory of weight loss, maintenance, and regain in adults; although it is commonly assumed that a period of maintenance follows initial weight loss prior to the onset of weight regain, our data demonstrate that weight regain began immediately for many participants, with a later decrease in the rate of regain. Given the development of new technologies and methods that allow for individual tailoring of interventions (e.g., just-in-time adaptive interventions delivered via mobile devices), an important next step is to identify the factors that more proximally predict the transition points at which people move from a weight loss trajectory to a weight regain trajectory and to investigate whether this pattern can be modified.O

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