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A limit on the energy transfer rate from the human fat store in hypophagia

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Abstract

A limit on the maximum energy transfer rate from the human fat store in hypophagia is deduced from experimental data of underfed subjects maintaining moderate activity levels and is found to have a value of (290 ± 25) kJ/kg d. A dietary restriction which exceeds the limited capability of the fat store to compensate for the energy deficiency results in an immediate decrease in the fat free mass (FFM). In cases of a less severe dietary deficiency, the FFM will not be depleted. The transition between these two dietary regions is developed and a criterion to distinguish the regions is defined. An exact mathematical solution for the decrease of the FFM is derived for the case where the fat mass (FM) is in its limited energy transfer mode. The solution shows a steady-state term which is in agreement with conventional ideas, a term indicating a slow decrease of much of the FFM moderated by the limited energy transferred from the fat store, and a final term showing an unprotected rapid decrease of the remaining part of the FFM. The average resting metabolic rate of subjects undergoing hypophagia is shown to decrease linearly as a function of the FFM with a slope of (249 ± 25) kJ/kg d. This value disagrees with the results of other observers who have measured metabolic rates of diverse groups. The disagreement is explained in terms of individual metabolic properties as opposed to those of the larger population.

Keywords: Weight loss; Energy transfer; Metabolism

1. Introduction

The popular assumption made in cases of hypophagia is that energy deficits are balanced by appropriate decreases in the fat mass (FM)[1] resulting in the initial constancy of the fat free mass (FFM). It is sometimes assumed that this situation will persist until the total exhaustion of the FM at which point the FFM will then begin to decrease. As reasonable as this paradigm may appear, it will be demonstrated that it is not valid in the case of semi-starvation where the FFM decreases from the start of the dietary regimen. It is deduced from the experimental data that, in the case of severe dietary restriction, the FM can only provide a limited rate of energy transfer to the FFM forcing the energy deficit to be made up by a decrease in the FFM. The ability of the FM to provide whatever energy is required by the FFM is possibly restricted by the rate limited biochemical reactions of the energy transfer processes. If, however, the dietary restriction is not severe, it is possible that "protein sparing" can occur at least until the FM is depleted to the level where its limited energy transfer capability becomes challenged. Both cases of "protein sparing" and "non-protein sparing" are discussed in this paper and the transition from the former condition to the latter is considered.

In order to demonstrate the immediate decrease of the FFM during severe dietary restriction, we make use of

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[1]In this paper, mass and weight are considered to be identical concepts measured in units of kilograms (kg).

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Nomenclature

ECW	extra cellular water, kg
FM	fat mass, kg
FFM	fat free mass, kg
RMR	resting metabolic rate, MJ/d
TBM	total body mass, kg
Q_{fd}	rate of ingested food energy, MJ/d
a	RMR multiplier of FFM, kJ/kg d (=(249±25) kJ/kg d)
b	RMR offset term, kJ/d
f	fat mass, kg (mnemonic, $f \approx$ fat)
f_0	initial FM, kg
f_{min}	minimum FM capable of sparing FFM, kg
ℓ	fat free mass, kg (mnemonic, $\ell \approx$ lean)
ℓ_{ss}	steady-state FFM, kg
t	time, d, week
Δ	energy deficiency term, MJ/d (defined in Eq. (4))
α	energy density of FM change, MJ/kg (=(39.2±1.7) MJ/kg)
β	energy density of FFM change, MJ/kg (=(8.56±1.67) MJ/kg)
δ	activity coefficient, kJ/kg d
ε	food utilization factor
σ'	maximum energy transfer factor, kJ/kg d (=(290±25) kJ/kg d)
σ	realizable energy transfer factor, kJ/kg d (decreased from maximum by activity coefficient)

data obtained in a humanitarian experiment done during wartime at the University of Minnesota by Keys et al. (1950). This experiment will be referred to as the Minnesota experiment (ME). In the ME, 32 young male volunteers of military status were semi-starved in order to evaluate optimal rehabilitation methods for use in treatment of the food deprived population of parts of wartime Europe. The data of the ME are used in this paper because of the long period of controlled semi-starvation (24 weeks), the multiple measurements of the FM, and the militarily mandated and enforced dietary compliance. Fortunately for this study, the average dietary restriction employed in the ME, (6.56±0.31) MJ/d, was nearly ideal for demonstrating the limit on the energy transfer rate from the FM.

In the ME, the FM was measured at three different times during the 24-week semi-starvation period by densitometric means and corrections were applied to take account of excess fluids and minerals. The corrected data were presented in tabular form without indication of experimental uncertainties. This author has taken the uncorrected data of the FM and has proportionally applied these stated errors directly to the reduced data which is presented in Fig. 1. The error bars in Fig. 1 are indicative of the standard error of the mean and should be considered to be minimal since they do not include the unknown uncertainties introduced by the correction process. A least squares fit was done on the experimental points resulting in the expression

$$f = 9.51\exp[-(t/135)], \tag{1}$$

where f is the FM in kg and t is the elapsed time in d. Eq. (1) is shown in Fig. 1 by the solid curve. The correlation coefficient for the fitting process was 0.9991. Also shown in Fig. 1 is the popular, non-dynamic concept (dashed line) that a constant energy deficit results in a fixed rate of decrease of the FM. The dotted–dashed curve in Fig. 1 indicates a dynamic

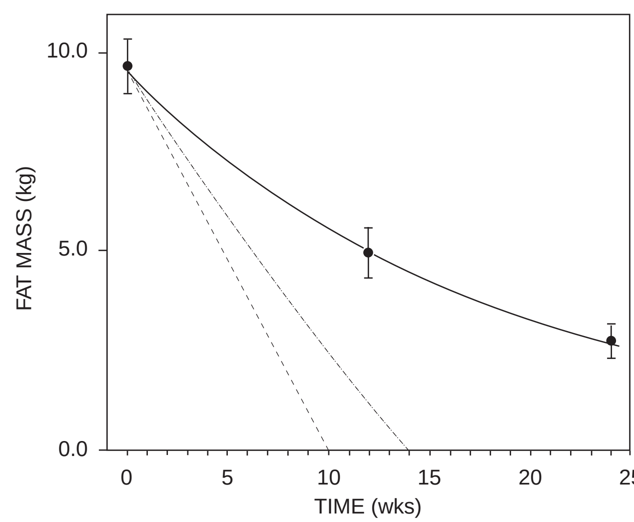

Fig. 1. The FM (kg) vs. time (weeks). The solid curve is an exponential least squares fit of the three averaged experimental data points. The straight dashed line represents the popular non-dynamic fat loss concept while the dotted–dashed curve is that for the dynamic concept of unlimited sparing of the FFM.

decrease of the FM based on the assumption that there is no limitation on the ability of the FM to transfer whatever energy is needed to the FFM. The equation for this curve will be derived in a later section of this paper and shows that the FM will be exhausted after 98 d of semi-starvation.

Point-by-point subtraction of the FM given by Eq. (1) from the experimental values of the total body mass (TBM) yields the results shown in Fig. 2 for the FFM during the semi-starvation period and for a few weeks prior to the beginning of the food energy restriction. There are three observations to be made from the data presented in Fig. 2. Firstly, there is an immediate decrease of the FFM. Secondly, the FFM reaches a constant value during the last 6 weeks of