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Dietary betaine intake is associated with skeletal muscle mass change over 3 years in middle-aged adults: the Guangzhou Nutrition and Health Study

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Abstract

A higher dietary intake or serum concentration of betaine has been associated with greater lean body mass in middle-aged and older adults. However, it remains unknown whether betaine intake is associated with age-related loss of skeletal muscle mass (SMM). We assessed the association between dietary betaine intake and relative changes in SMM after 3 years in middle-aged adults. A total of 1242 participants aged 41–60 years from the Guangzhou Nutrition and Health Study 2011–2013 and 2014–2017 with body composition measurements by dual-energy X-ray absorptiometry were included. A face-to-face questionnaire was used to collect general baseline information. After adjustment for potential confounders, multiple linear regression found that energy-adjusted dietary betaine intake was significantly and positively associated with relative changes (i.e. percentage loss or increase) in SMM of legs, limbs and appendicular skeletal mass index (ASMI) over 3 years of follow-up (β 0·322 (SE 0·157), 0·309 (SE 0·142) and 0·303 (SE 0·145), respectively; $P < 0·05$). The ANCOVA models revealed that participants in the highest betaine tertile had significantly less loss in SMM of limbs and ASMI and more increase in SMM of legs over 3 years of follow-up, compared with those in the bottom betaine tertile (all $P_{trend} < 0·05$). In conclusion, our findings suggest that elevated higher dietary betaine intake may be associated with less loss of SMM of legs, limbs and ASMI in middle-aged adults.

Key words: Dietary betaine: Skeletal muscle mass: Skeletal muscle index: Longitudinal change: Prospective cohort studies

Population ageing is accelerating all over the world[1]. Maintaining functional ability is the core of healthy ageing[2]. Skeletal muscle is required for physical performance in daily life[3]. The decline in skeletal muscle mass (SMM) begins as early as 35 years of age and accelerates after 60 years[4]. Age-related loss of skeletal muscle, which leads to the onset of sarcopenia in severe cases, can increase the risk of functional impairment and mortality[5–7]. It is worthy to note that muscle mass reduction is an important feature of 'pre-sarcopenia'[8]. A life-course model of preventing sarcopenia[9] focuses on maximising peak muscle mass and strength in early life, maintaining peak muscle mass and strength in adult life and minimising muscle loss in older life[10], which means early prevention is important and necessary for the prevention of sarcopenia. In addition to physical inactivity and inadequate dietary protein[8], few modifiable factors have been identified.

Betaine serves as an important methyl donor [11] in the transformation of homocysteine into methionine[12], which could promote muscle protein synthesis by decreasing homocysteine thiolactone and thus activating the insulin-like growth factor-1 pathway[13]. Betaine could improve lean meat percentage of pig carcasses when restricting energy and protein intake[14–16], and thus is widely added to animal feeds to increase lean meat in livestock[17–19]. In recent years, the role of betaine in maintaining muscle mass in humans has been a focus of attention. Our previous cross-sectional study found that middle-aged and older men with higher serum betaine levels had a higher percentage of lean mass and a lower likelihood of low lean mass[20]. Consistently, cross-sectional studies from Newfoundland[21] found that higher circulating betaine was associated with greater lean body mass. Given that the existing observational studies are primarily cross-sectional and only consider circulating betaine,

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Abbreviations: ASMI, appendicular skeletal mass index; GNHS, Guangzhou Nutrition and Health Study; MET, metabolic equivalents; SMM, skeletal muscle mass.

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further longitudinal studies are still needed to clarify the relationship between dietary betaine intake and skeletal muscle loss in middle-aged adults.

Therefore, this prospective cohort study aimed to investigate whether dietary betaine intake was associated with SMM change after 3 years of follow-up in community-dwelling middle-aged Chinese adults. We hypothesised that higher dietary betaine intake may be beneficial for maintaining SMM among middle-aged adults.

Methods

Study population

Data for this analysis are from the Guangzhou Nutrition and Health Study (GNHS), an ongoing, community-based prospective cohort study investigating the determinants of cardiometabolic outcomes and osteoporosis in middle-aged and older Chinese adults[22]. The GNHS was established during 2008–2010, enrolling 3169 apparently healthy men and women aged 40–80 years living in the communities of Guangzhou, China, for at least 10 years. Of them, 2520 participants completed the first follow-up during 2011–2013. Meanwhile, another 879 participants were newly recruited in 2013. Therefore, a total of 3399 participants took part in the GNHS 2011–2013. After excluding 1920 older adults (aged ≥60 years), 1479 middle-aged adults (aged 41–60 years) were assessed for eligibility in this analysis and 1401 of whom completed the second follow-up occurring between the years 2014 and 2017. Face-to-face interviews were conducted to collect information on sociodemographic characteristics, lifestyles and food consumption in GNHS 2008–2010 and GNHS 2011–2013. Body composition measurements by whole-body dual-energy X-ray absorptiometry were performed in GNHS 2011–2013 and GNHS 2014–2017. Written informed consent was provided by all participants. All protocols were approved by the Ethics Committee of the School of Public Health at Sun Yat-sen University.

Because dual-energy X-ray absorptiometry scans were first administered in GNHS 2011–2013, that visit served as the study baseline for this analysis, and only those participants who attended both GNHS 2011–2013 and GNHS 2014–2017 were eligible for inclusion (n 1401). In the present study, 159 participants were excluded due to (1) severe metabolic diseases, including malignant neoplasms, liver cirrhosis, renal insufficiency, diabetes and chronic hepatitis; (2) missing values for body composition measurements in either GNHS 2011–2013 or GNHS 2014–2017; (3) missing dietary data or covariates (e.g. physical activity, age); (4) extreme intake of energy (men, <3347 kJ/d (<800 kcal/d) or >16 736 kJ/d (>4000 kcal/d); women, <2092 kJ/d (<500 kcal/d) or >14 644 kJ/d (>3500 kcal/d)) or dietary betaine (the top and bottom 0·5 % of the betaine intake) and (5) abnormal weight or weight change >15 % over 3 years of follow-up. Finally, 1242 participants were included for analysis (Fig. 1). All participation was voluntary, and all of them provided written informed consent. The study was approved by the Ethics Committee of the School of Public Health at Sun Yat-sen University and was conducted according to the Declaration of Helsinki.

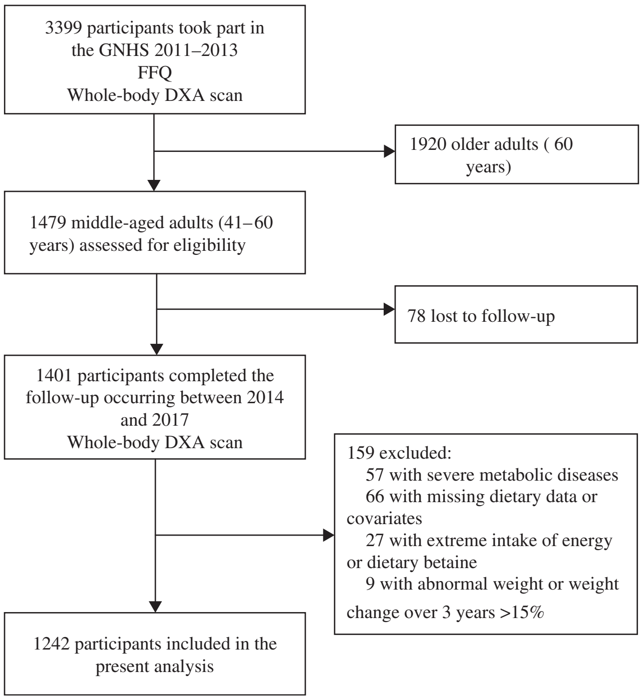

Fig. 1. Flow chart of selection of participants from the Guangzhou Nutrition and Health Study (GNHS) for the analysis of dietary betaine intake and changes in skeletal muscle mass over 3 years. DXA, dual-energy X-ray absorptiometry.

Skeletal muscle mass

Body composition was assessed in GNHS 2011–2013 and GNHS 2014–2017 by using dual-energy X-ray absorptiometry (Discovery W; Hologic Inc) according to standard procedures. Dual-energy X-ray absorptiometry calibration was performed daily with a standard phantom. Lean mass, fat mass and bone mass of the whole body, trunk, arms and legs were analysed using the Hologic Discovery software version 3.2. We assumed that all non-fat and non-bone tissue were skeletal muscle in arms and legs, thus SMM of the arms and legs was determined by subtracting bone mineral content from the total lean mass. SMM of the limbs was calculated as the sum of the SMM in arms and legs. The methods and validation data (the intraclass correlation coefficient for the test-retest reliability of the appendicular SMM measurement was 0·98 (95 % CI 0·96, 0·99)) have been reported previously[23]. The appendicular skeletal mass index (ASMI, kg/m^2) was defined by dividing SMM of the limbs in kg by the square of height in metres[24]. Relative changes in SMM of arms, legs and limbs or ASMI were calculated following the formula:

Relative change in SMM or ASMI = ((SMM or ASMI in GNHS 2014–2017) – (SMM or ASMI in GNHS 2011–2013))/(SMM or ASMI in GNHS 2011–2013) × 100 %.

Dietary assessment

A paper-based seventy-nine-item semi-quantitative FFQ[25] was used to collect dietary information in GNHS 2011–2013. For each food item, frequency (i.e. never, per year, per month, per week or per d) and amount of food consumption (servings or portion sizes) were recorded. Pictures of common foods and serving sizes were provided to help participants estimate their usual food consumption in the previous year. The participants' daily nutrient and energy intake were calculated according to the China Food Composition Table 2004[26]. Betaine comes mainly from plant foods such as beets, wheat bran, wheat germ, spinach, pretzels, wheat bread and crackers. Dietary betaine intake was determined according to the food composition data obtained from Zeisel *et al.*[27] and the US Department of Agriculture Database[28]. Nutrient intake was adjusted for total energy intake using the residual method proposed by Willett & Stampfer[29].

Covariates

Weight and height were measured with the participant's barefoot and wearing light clothes. BMI (kg/m^2) was calculated as body weight in kilograms divided by the square of height in metres. Waist circumference was measured twice, and the average value was used for subsequent analyses. An interviewer-administered questionnaire was used to collect the following information in GNHS 2011–2013: sociodemographic characteristics (e.g. age, sex); general lifestyles and chronic disease history and medicine use. Daily physical activity[30], including occupation, transportation, exercise, leisure-time sedentary activity and housework, was estimated using a nineteen-item questionnaire and was classified into three categories according to tertiles of daily total metabolic equivalents: low (<0·05 metabolic equivalents × h/d), medium (0·05–3·86 metabolic equivalents × h/d) and high (>3·86 metabolic equivalents × h/d) intensity.

Statistical analysis

The interactions between betaine intake and sex on relative changes in SMM were not significant (all $P > 0·05$). Therefore, all analyses were carried out in the total population. Baseline characteristics of the study population were compared across tertiles (T) of energy-adjusted dietary betaine intake by using one-way ANOVA or Pearson's χ^2 test, where appropriate. Continuous data are summarised as mean values and standard deviations. Categorical data are reported as frequencies and percentages. Energy-adjusted dietary betaine intake was evaluated as both a continuous and a categorical variable by using tertiles (medians: T1, 145·8 (range 49·7–195·6) mg/d; T2, 241·4 (range 196·5–285·5) mg/d; T3, 361·3 (range 286·8–759·3) mg/d). Multiple linear regression models and ANCOVA were used to examine the associations between dietary betaine intake and relative changes in SMM of arms, legs, limbs and ASMI, respectively. Model 1 was adjusted for age, sex, energy intake, baseline SMM or ASMI, waist circumference and height. Model 2 was adjusted additionally for physical activity level, protein intake, choline intake and use of multivitamins. *Post hoc* comparisons were conducted by using Bonferroni corrections. Tests for a linear trend across tertiles of dietary betaine intake were conducted by using the median value in each tertile as a continuous variable in the linear regression models.

All tests were two-sided, and *P* values <0·05 were considered significant. All analyses were performed using SPSS version 23.0 (IBM Corp.)[31].

Results

Participant characteristics

A total of 294 men and 948 women were included in this analysis. The mean age of the participants was 56·1 (SD 3·1) years. Mean energy and energy-adjusted dietary betaine intake were 7594 (SD 2033) kJ/d (1815 (SD 486) kcal/d) and 259·0 (SD 120·1) mg/d.

Table 1 presents the descriptive characteristics of the study population by tertiles of energy-adjusted dietary betaine intake in the GNHS 2011–2013. There was a similar proportion of men and women in each tertile of betaine intake. Although there were no significant differences in body weight, height and waist circumference across tertiles of dietary betaine intake, middle-aged adults with a higher dietary betaine intake had a higher BMI ($P = 0·039$). Daily dietary intake of energy and protein, as well as physical activity level, did not differ significantly between participants with different dietary betaine intakes in middle-aged adults. Nevertheless, a higher dietary choline intake was observed to be associated with a higher betaine intake. SMM of arms, legs, limbs and ASMI in the GNHS 2011–2013 was comparable across the tertiles of betaine intake, and all of them have no significant difference.

Table 2 shows crude changes in SMM and ASMI over 3 years. SMM of arms, legs, limbs and ASMI decreased with advancing age. Relative change in SMM of arms, legs, limbs and ASMI was −2·25 (SD 6·19), −1·28 (SD 5·70), −1·55 (SD 5·10) and −1·20 (SD 5·20) % over 3 years of follow-up.

Associations between betaine intake and relative changes in skeletal muscle mass

The associations between dietary betaine intake and relative changes in SMM of arms, legs, limbs and ASMI were examined by using both continuous and categorical betaine variables. The results obtained from the multiple linear regression (continuous) and the ANCOVA (categorical) models were highly consistent.

Adjusted regression coefficients for relative changes in SMM of arms, legs, limbs and ASMI per 1 SD of energy-adjusted dietary betaine intake in middle-aged adults are summarised in Table 3. After adjustment for age, sex, energy intake, baseline SMM or ASMI, waist circumference and height, dietary betaine intake was significantly associated with relative changes in SMM of legs, limbs and ASMI over 3-year follow-up (β: 0·311 (SE 0·155), 0·301 (SE 0·140) and 0·301 (SE 0·143) in model 1, respectively; all $P < 0·05$). The associations between dietary betaine intake and relative changes in SMM of legs, limbs and ASMI remained significant after additional adjustment for physical activity level, protein intake, choline intake and use of multivitamins (β: 0·322 (SE 0·157), 0·309 (SE 0·142) and 0·303 (SE 0·145) in model 2, respectively; all $P < 0·05$). No significant associations were observed between dietary betaine intake and relative change in SMM of arms ($P > 0·05$).

Table 4 and Fig. 2 show adjusted means (SE or 95 % CI) of relative changes in SMM of arms, legs, limbs and ASMI by tertiles of dietary betaine intake, after adjustment for sex, age, energy intake, baseline SMM or ASMI, height, waist circumference, physical activity level, protein intake, choline intake and use of multivitamins. Participants in the highest tertile of dietary

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Table 1. Descriptive characteristics of 1242 middle-aged adults (41–60 years) by tertiles (T) of energy-adjusted dietary betaine intake in the Guangzhou Nutrition and Health Study 2011–2013
(Mean values and standard deviations; numbers and percentages)

	Energy-adjusted dietary betaine intake						
	T1 (*n* 414)		T2 (*n* 414)		T3 (*n* 414)		
	Mean	SD	Mean	SD	Mean	SD	*P*
Age (years)	55·9	3·1	56·2	3·0	56·1	3·1	0·311
Weight (kg)	58·3	10·0	58·7	9·0	59·6	9·6	0·133
Height (cm)	158·9	7·3	158·5	7·3	159·0	7·0	0·584
BMI (kg/m^2)	23·0	3·0	23·4	2·9	23·5	3·2	0·039
Waist circumference (cm)	83·4	8·4	83·8	8·6	84·3	8·8	0·313
Daily dietary intake							
Energy (kcal/d)*	1816	509	1827	474	1802	475	0·772
Protein (g/d)†	75·5	10·8	74·9	9·6	76·3	9·8	0·156
Betaine (mg/d)†	142·9	37·0	240·7	24·9	393·4	96·8	<0·001
Choline (mg/d)†	259·1	78·9	269·9	70·9	283·0	78·4	<0·001
Skeletal muscle mass							
Arms (kg)	3·8	1·1	3·8	1·0	3·8	1·1	0·432
Legs (kg)	12·2	2·6	12·1	2·5	12·4	2·6	0·269
Limbs (kg)	15·9	3·6	15·9	3·4	16·2	3·6	0·303
ASMI (kg/m^2)	6·3	1·0	6·3	1·0	6·4	1·0	0·204
	n	%	*n*	%	*n*	%	
Men	99	23·9	93	22·5	102	24·6	0·561
Married	361	87·2	373	90·1	367	88·6	0·421
Use of multivitamins	105	25·4	111	26·8	116	28·0	0·688
Physical activity level							
Low	139	33·6	141	34·1	134	32·4	0·672
Middle	139	33·6	149	36·0	136	32·9	
High	136	33·3	124	30·0	144	34·8	

ASMI, appendicular skeletal muscle index.
* To convert energy values from kcal to kJ, multiply by 4·184.
† Nutrient intake was adjusted for energy intake using the residual method.

Table 2. Crude changes in skeletal muscle mass (SMM) and appendicular skeletal mass index (ASMI) of 1242 middle-aged adults (41–60 years) between Guangzhou Nutrition and Health Study (GNHS) 2011–2013 and GNHS 2014–2017
(Mean values and standard deviations)

	GNHS 2011–2013		GNHS 2014–2017		Change*		Relative change (%)†	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Arms (kg)	3·78	1·05	3·69	1·04	–0·09	0·24	–2·25	6·19
Legs (kg)	12·22	2·55	12·06	2·60	–0·16	0·71	–1·28	5·70
Limbs (kg)	16·01	3·54	15·76	3·58	–0·25	0·84	–1·55	5·10
ASMI (kg/m^2)	6·30	0·97	6·22	1·00	–0·08	0·33	–1·20	5·20

* Change = (SMM or ASMI in GNHS 2011–2014) – (SMM or ASMI in GNHS 2014–2017).
† Relative change = change/(SMM or ASMI in GNHS 2011–2014) × 100 %.

betaine intake had significantly less loss in SMM of limbs and ASMI and more increase in SMM of legs over 3 years of follow-up than those in the lower two betaine tertiles (all $P < 0{\cdot}05$). A significant dose-dependent reduction in loss of leg and limb SMM and ASMI was observed with the increase of dietary betaine intake (all $P_{trend} < 0{\cdot}05$). However, there were neither significant differences in relative change in SMM of arms across tertiles of dietary betaine intake (all $P > 0{\cdot}05$) nor significant linear association between loss of arm SMM and dietary betaine intake ($P_{trend} = 0{\cdot}116$).

Discussion

Previous cross-sectional studies have showed that higher betaine intakes or higher serum betaine levels were associated with greater lean body mass in middle-aged and older adults. However, few longitudinal studies have investigated whether higher betaine intake is beneficial for preventing age-related loss of SMM. To our knowledge, this is the first prospective cohort study examining the association between dietary betaine intake and changes in SMM among community-dwelling middle-aged adults. In the GNHS cohort, a higher dietary betaine intake was associated with less loss in SMM of legs and limbs and ASMI over 3 years of follow-up in middle-aged adults. Of note, middle-aged adults in the highest tertile of betaine intake even experienced an increase in SMM of legs and limbs and ASMI during the 3-year follow-up.

There is strong biological plausibility for the association between betaine and changes in SMM. First, homocysteine thiolactone can inhibit insulin/insulin-like growth factor-1 mediated

Table 3. Relative change (Δ)* in skeletal muscle mass (SMM) and appendicular skeletal mass index (ASMI) per 1 SD of energy-adjusted dietary betaine intake in middle-aged adults from the Guangzhou Nutrition and Health Study (GNHS)
(Adjusted regression coefficients with their standard errors)

	Energy-adjusted dietary betaine intake		
	β	SE	*P*
ΔSMM of arms			
Model 1†	0·316	0·172	0·066
Model 2‡	0·327	0·174	0·060
ΔSMM of legs			
Model 1†	0·311	0·155	0·045
Model 2‡	0·322	0·157	0·040
ΔSMM of limbs			
Model 1†	0·301	0·140	0·032
Model 2‡	0·309	0·142	0·029
ΔASMI			
Model 1†	0·301	0·143	0·035
Model 2‡	0·303	0·145	0·036

* Relative change (Δ) in SMM or ASMI = ((SMM or ASMI in GNHS 2014–2017) – (SMM or ASMI in GNHS 2011–2013))/(SMM or ASMI in GNHS 2011–2013) × 100 %.
† Model 1 was adjusted for age, sex, energy intake, baseline SMM or ASMI, waist circumference and height.
‡ Model 2 was adjusted for variables in model 1 + physical activity level, protein intake, choline intake and use of multivitamins.

Table 4. Relative change (%) in skeletal muscle mass (SMM) and appendicular skeletal mass index (ASMI)*† over 3 years estimated by tertiles (T) of energy-adjusted dietary betaine intake
(Adjusted mean values with their standard errors)

	T1		T2		T3		
	Mean	SE	Mean	SE	Mean	SE	P_{trend}
ΔSMM of arms	–1·450	0·390	–1·306	0·393	–0·791	0·394	0·116
ΔSMM of legs	–0·304	0·330	–0·229	0·329	0·620‡	0·330	0·013
ΔSMM of limbs	–0·739	0·305	–0·659	0·305	0·102‡	0·306	0·013
ΔASMI	–0·453	0·308	–0·348	0·309	0·357‡	0·310	0·019

* Relative change (Δ) in SMM or ASMI = ((SMM or ASMI in GNHS 2014–2017) – (SMM or ASMI in GNHS 2011–2013))/(SMM or ASMI in GNHS 2011–2013) × 100 %.
† Adjusted for age, sex, energy intake, baseline SMM or ASMI, waist circumference, height, physical activity level, protein intake, choline intake and use of multivitamins.
‡ The values in T3 were significantly different from the values in T1 and T2.

mRNA expression and enzyme activity involved in protein synthesis. Betaine can reduce the production of homocysteine thiolactone through the remethylation of homocysteine to methionine, thereby enhancing protein synthesis in skeletal muscle[13]. Second, betaine can promote muscle fibre differentiation and increases myotube size by activating the insulin-like growth factor-1 pathway[32]. Third, accumulation of betaine in cells during metabolism leads to an increase in sarcoplasmic osmolality via the osmoregulated betaine/GABA transporter-1, resulting in cellular swelling. Cellular swelling can promote protein synthesis and suppresses proteolysis through enhancing amino acid uptake or inducing a series of cascades via activating mitogen-activated protein kinase[33]. Fourth, betaine as a methyl donor provides its labile methyl groups for the synthesis of carnitine and creatine[34], which have been used to increase muscle mass in community-dwelling adults older than 55 years[35,36].

Although our study showed that a higher dietary betaine intake was significantly associated with a reduction in SMM loss over 3 years, betaine ingestion was not associated with SMM of arms, legs, limbs and ASMI at baseline. These findings were inconsistent with the findings from previous cross-sectional studies. Higher serum betaine levels have been observed to be associated with greater lean body mass in male adults who participated in the GNHS study and the CODING (Complex Disease in Newfoundland population: Environment and Genetics) study[20,21]. Humans obtain betaine either from foods that contain betaine or by de novo synthesis of betaine in the body. Serum betaine, as a biomarker of internal exposure of betaine, is a more accurate measurement of betaine status than dietary betaine intake. However, since serum betaine concentrations were not assessed in the GNHS 2011–2013, we could not explain whether the inconsistent results are due to the selection of different exposure markers (i.e. dietary or serum betaine) or not. In contrast, another cross-sectional study using data from the CODING study reported that higher dietary betaine intakes were significantly related to greater total percentage lean mass[37]. Notably, dietary betaine intake is much lower in the CODING study than in our study (110·1 *v.* 259·0 mg/d). There may be a ceiling effect of betaine intake on muscle growth when betaine intake reaches a certain level. On the other hand, we assessed the association between dietary betaine intake expressed as mg/d and SMM of arms, legs and limbs, while the CODING study investigated the association between dietary betaine intake expressed as mg/kg per d and total body lean mass. Both the confounding effect of body weight and different muscle outcomes used may contribute to the inconsistent findings.

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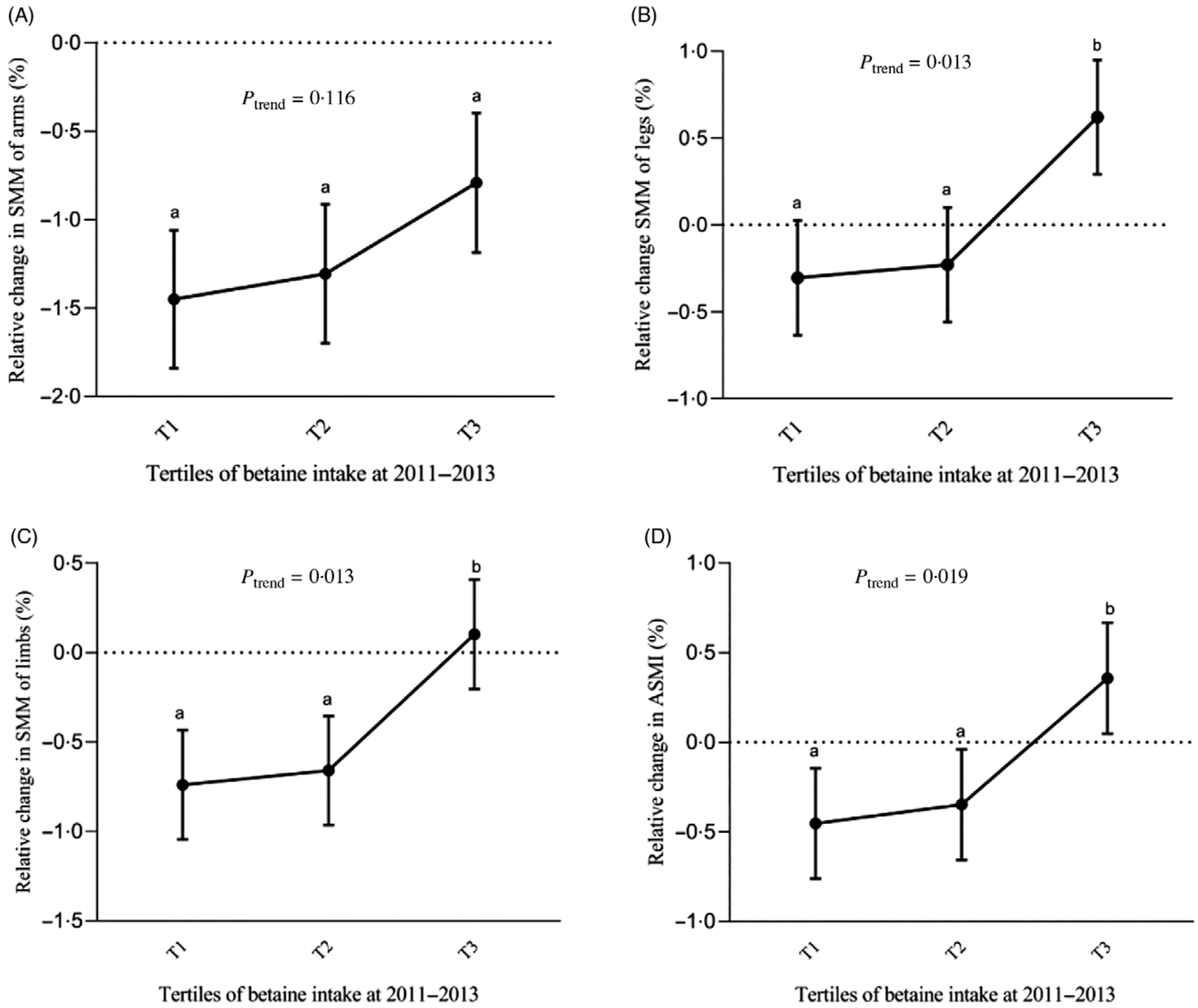

Fig. 2. Adjusted relative change in skeletal muscle mass (SMM) of arms (A), legs (B), limbs (C) and appendicular skeletal muscle index (ASMI) (D) over 3 years by tertiles (T) of energy-adjusted dietary betaine intake in middle-aged (age < 60 years) adults from the Guangzhou Nutrition and Health Study. Adjusted for sex, age, energy intake, baseline SMM or ASMI, height, waist circumference, physical activity level, protein intake, choline intake, marital status and use of multivitamins. Tests for a linear trend across tertiles of dietary betaine intake were conducted by using the median value in each tertile as a continuous variable in the linear regression models. [a,b] Least-squares means with unlike letters are significantly different ($P < 0·05$; *t* test). Median energy-adjusted dietary betaine intake by tertile (from T1 to T3) was 145·8, 241·4 and 361·3 mg/d.

There are several strengths to the study. First, the present study was a prospective cohort study with a relatively large sample size. Second, the long follow-up (3 years) allowed us to observe the changes in SMM over time and to examine the association between dietary betaine and relative change in SMM. Third, detailed information on sociodemographic information and physical activity was collected, which was later used as covariates in the statistical model.

Some limitations must be acknowledged as well. First, we used self-reported FFQ to collect dietary information which raises the possibility of recall bias and misreporting of food consumption. However, photographs of generic foods and portion sizes were provided to help participants estimate their usual food consumption. Another defect is that we had little information on muscle function in this population. We could not infer the relationship between dietary betaine and muscle strength or performance. Third, although we have carefully adjusted for potential confounders including physical activity and energy and protein intake, residual confounding cannot completely be ruled out since the age-related loss of SMM might be influenced by a variety of genetic and environmental factors. Fourth, the lack of betaine biomarker precludes us from reaching a sound conclusion of betaine status and SMM loss. Besides, we had no information on changes in diets and physical activity during the follow-up, since dietary assessment and physical activity questionnaire were only performed in GNHS 2011–2013. And last, the observational nature of the present study precludes us from estimating a causal association between dietary betaine intake and changes in SMM.

Conclusion

Higher dietary betaine intake was associated with less loss of SMM in middle-aged adults, suggesting that increasing dietary betaine intake may help maintain or improve SMM during ageing. Further long-term prospective studies, especially randomised controlled trials, are needed to confirm the findings.

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The authors declare that there are no conflicts of interest.

Supplementary material

For supplementary material referred to in this article, please visit https://doi.org/10.1017/S0007114520002433

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