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Socioeconomic Inequalities in Biological Aging: The Mediating Roles of Diet and Leisure-Time Physical Activity in a Prospective Cohort

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Highlights

What are the main findings?

- Higher baseline socioeconomic status was associated with lower biological age acceleration at follow-up after adjustment for baseline BAA.
- Diet and leisure-time physical activity may each partly mediate the association between socioeconomic status and follow-up biological age acceleration.

What are the implications of the main findings?

- Socioeconomic disadvantage may help identify groups with higher biological age acceleration at follow-up.
- Studies with clearer temporal ordering could evaluate potential pathways through diet and LTPA and inform randomized controlled trials testing whether dietary or physical activity interventions can reduce socioeconomic inequalities in BAA.

Abstract

Background: Socioeconomic status (SES) has been linked to biological age acceleration (BAA), suggesting that health inequalities may emerge before age-related diseases become apparent. However, prospective non-Western evidence remains limited and underlying mechanisms are understudied. Therefore, we examined the association between SES and BAA in a prospective Chinese cohort and assessed diet and leisure-time physical activity (LTPA) as potential mediators. **Methods**: This prospective analysis included 9080 participants from the China Multi-Ethnic Cohort with baseline and follow-up data. SES was classified using latent class analysis of education, annual household income, and occupation. BAA was estimated using the Klemera-Doubal method. Multivariable linear regression models and counterfactual mediation analysis were conducted. **Results**: The mean age was 51.32 (10.75) years and 61.8% were women. In longitudinal analyses, higher SES was associated with lower follow-up BAA. Specifically, compared with low SES, middle and high SES were associated with lower follow-up BAA ($\beta = -0.45$, 95% CI: −0.75 to −0.14; $\beta = -0.91$, 95% CI: −1.29 to −0.53, respectively). Diet and LTPA may each partially mediate these associations, accounting for 14.2% and 10.0% of the effect for middle versus low SES,

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Academic Editors: Elena S. Rotarou, Ximena Moreno and Omar Ramos-Lopez

Received: 14 October 2026
Revised: 24 November 2026
Accepted: 25 November 2026
Published: 27 November 2026

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and 5.2% and 6.0% for high versus low SES, respectively. **Conclusions**: Higher SES was associated with lower follow-up BAA. Diet and LTPA may partially mediate this association. Studies with clearer temporal ordering could evaluate these potential pathways and inform the design of randomized controlled trials.

Keywords: socioeconomic status; biological age; diet; leisure-time physical activity; mediation analysis

1. Introduction

As populations age rapidly worldwide, the growing burden of non-communicable diseases, disability, and functional decline has become a major challenge. These adverse health outcomes are unequally distributed, with socioeconomically disadvantaged populations consistently bearing a greater burden of poor health in later life [1,2]. However, socioeconomic differences in age-related health may begin to emerge before obvious disease. Biological aging involves a gradual loss of physiological function and resilience across organ systems. Processes such as cellular senescence, mitochondrial dysfunction, and chronic low-grade inflammation can contribute to this decline [3]. Biological age (BA) summarizes aspects of this process by expressing an individual's biomarker profile in age units [4,5]. Different methods use different sets of biomarkers, including DNA methylation markers and routine clinical measurements [4,5]. The Klemera–Doubal method (KDM) estimates BA using the relationships between clinical biomarkers and chronological age (CA) [6]. The KDM BA summarizes variation in physiological status. Biological age acceleration (BAA) is defined as BA minus CA. A positive BAA indicates an older biomarker profile relative to CA at the time of measurement; vice versa. Greater BAA has been associated with adverse health outcomes, and it may help characterize how socioeconomic disadvantage relates to chronic disease and mortality [7,8].

Accumulating evidence suggests that lower socioeconomic status (SES) is associated with greater BAA [9–14]. For instance, participants in a lower household income bracket had approximately 0.7 years greater PhenoAge acceleration than those in the highest income bracket [10]. Analyses of the UK Biobank and the US National Health and Nutrition Examination Survey (NHANES) also linked less favorable social conditions to greater BAA [7]. However, existing evidence is largely derived from cross-sectional studies in Western populations, limiting both generalizability to rapidly aging non-Western settings and temporal interpretation.

In addition, the mechanism behind the association between SES and BAA remains uncertain. Based on previous studies, diet and leisure-time physical activity (LTPA) may be two plausible behavioral pathways. Existing evidence shows that socioeconomic factors can influence food choices, and higher SES is associated with better diet quality [15,16]. Better diet is associated with lower BAA, with systemic inflammation and blood lipid profiles implicated as potential mechanisms [17]. Socioeconomic circumstances may also shape opportunities for LTPA, including access to recreational facilities [18]. In a national survey of Chinese adults, LTPA was more common among those with higher education or income [19]. Lipid profiles partly accounted for the association between physical activity and BAA, suggesting a potential metabolic pathway [20]. To conclude, diet and LTPA are both affected by SES and associated with BAA. However, evidence on their mediating roles between SES and BAA remains scarce.

To address these gaps, we examined the prospective association between SES and follow-up BAA in a Chinese cohort and evaluated the potential mediating roles of diet and LTPA in this association.

2. Materials and Methods

2.1. Study Design and Population

The China Multi-Ethnic Cohort (CMEC) is an ongoing population-based prospective cohort conducted in Southwest China [21]. The baseline survey was conducted between 2018 and 2019 in five provinces, enrolling 99,556 participants using a multistage, stratified cluster sampling design. The first follow-up survey was conducted between 2020 and 2021, and most participants were drawn from the baseline cohort. The sampling procedures aimed to match the age and sex distributions of the respective local populations as closely as possible. Standardized questionnaires, physical examinations and laboratory tests were performed at both time points.

The CMEC cohort specified an eligible age range of 30–79 years at baseline. For the present analysis, we included participants who met this criterion, completed both surveys and had available biomarker data required for BA estimation. Individuals with missing information on SES, mediators, or covariates were also excluded. The final analytic sample comprised 9080 participants. The detailed participant selection process is presented in Figure 1. The comparison of the baseline characteristics of included and excluded participants can be found in Table S1. Variable-specific missingness among excluded participants is reported in Table S2.

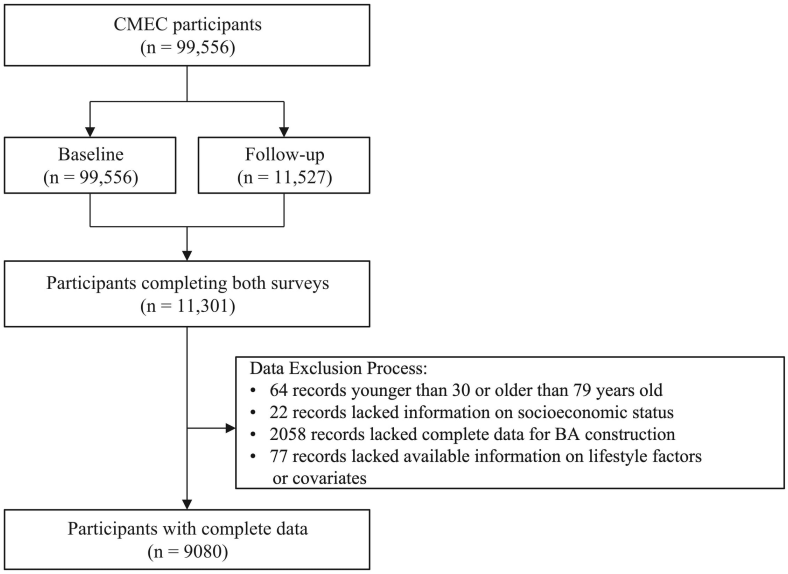

Figure 1. Flow chart of participant selection for the present study.

The CMEC study was approved by the Medical Ethics Review Committee of Sichuan University (K2016038, K2020022), and all participants provided written informed consent.

2.2. Assessment of Biological Age and Biological Age Acceleration

BA was estimated using the Klemera-Doubal method (KDM), a validated composite aging measure derived from clinical biomarkers [6]. Candidate biomarkers were initially selected based on their functional relevance to physiological systems, evidence from previous studies and data availability [22,23]. A Box–Cox transformation was then performed for each available biomarker to improve normality [24,25]. Next, biomarkers associated with CA were retained ($|r| > 0.1$), and redundant indicators providing overlapping information were excluded to minimize collinearity ($|r| > 0.7$) [22]. The final set of biomarkers included systolic blood pressure (SBP), waist-to-hip ratio (WHR), peak expiratory flow (PEF), low-density lipoprotein cholesterol (LDL-C), high-density lipoprotein cholesterol (HDL-C), glycated hemoglobin (HbA1c), triglycerides (TG), aspartate aminotransferase

(AST), gamma-glutamyl transferase (GGT), albumin (ALB), alkaline phosphatase (ALP), creatinine, urea, and mean corpuscular volume (MCV).

BA was calculated using the BioAge package in R, which implements the KDM algorithm by integrating biomarker–age regression relationships estimated in the reference population. In the present study, model parameters were trained using baseline data and then applied to both baseline and follow-up measurements using the same set of biomarkers and coefficients. More details of BA construction are provided in Supplementary Text S1 and Tables S3–S7. BAA was defined as the difference between BA and CA (BAA = BA − CA), and should not be interpreted as a direct measure of the rate of biological aging [26]. To describe the magnitude and dispersion of differences between the calculated BA and CA, we generated Bland–Altman plots for the total population and stratified by sex (Figures S1–S3). We also examined the cross-sectional associations of BAA with prevalent major chronic diseases and found that an increase in BAA was associated with higher odds of prevalent cardiovascular disease, hypertension, diabetes, and COPD (Table S8).

2.3. Assessment of Socioeconomic Status

SES was assessed using three indicators at baseline: education, annual household income, and occupation. Education was categorized into three levels: low (less than high school), middle (high school or equivalent), and high (college or above). Annual household income was grouped into approximate tertiles of the observed income distribution: low (<RMB 20,000), middle (RMB 20,000–59,999), and high (≥RMB 60,000). For education and income, categories were coded as 1 (low), 2 (middle), and 3 (high), with higher scores indicating a more advantaged SES [27,28]. Occupation was coded as 1 for unemployed individuals, 2 for workers and farmers, 3 for businessmen or clerks, 4 for professionals, managers, or government employees and 5 for retirees. The occupational codes served as nominal category labels.

To capture the multidimensional nature of SES, latent class analysis (LCA), a statistical approach that identifies unobserved subgroups [29] was applied to these three indicators. Based on model fit indices and substantive interpretability, three latent classes were identified and interpreted as representing low, middle, and high SES (Tables S9 and S10). We treated the assigned classes as fixed in the regression and mediation analyses. Details can be found in Supplementary Text S2.

2.4. Assessment of Mediators

Diet at baseline was assessed using a food frequency questionnaire (FFQ), which collected information on habitual consumption during the previous year, including intake frequency and quantity. Diet was evaluated using the alternative Mediterranean diet (aMED) score to represent adherence to a Mediterranean-style dietary pattern [30–33] following the approach previously applied in the CMEC [34]. The score included eight components: vegetables, legumes, fruit, whole grains, fish and seafood, the ratio of monounsaturated to saturated fatty acids, red and processed meat, and alcohol. Nuts were excluded because the CMEC questionnaire did not assess them separately. Participants were categorized into quintiles for each dietary component and assigned scores from 1 to 5 according to intake levels. Alcohol was scored separately from 1 to 5 using sex-specific categories of ethanol intake. The eight component scores were summed to yield a range of 8–40, with higher scores indicating better adherence to a Mediterranean-style diet. For the sensitivity analysis, we calculated a modified Dietary Approaches to Stop Hypertension (DASH) score to assess adherence to a DASH-style dietary pattern. The detailed scoring procedures for both the aMED and DASH scores can be found in a previously published article [34].

LTPA at baseline was assessed using a structured questionnaire adapted from previously validated instruments [35,36]. Participants reported the usual type, frequency, and duration of activities performed during the previous year. The intensity of each activity was assigned according to metabolic equivalent task (MET) values reported in the literature [35]. In this study, LTPA was classified as active (≥7.5 MET-hours/week) or inactive (<7.5 MET-hours/week) [37].

2.5. Assessment of Covariates

Information on covariates was collected using standardized questionnaires administered during the baseline survey. These variables included sex, CA, ethnicity, marital status, and urbanicity. Marital status was classified as accompanied (married or cohabiting) or unaccompanied (separated, divorced, widowed, or never married). Baseline BAA was also included as a covariate to account for individual differences in initial biological aging status.

2.6. Statistical Analysis

Baseline characteristics of participants were described according to SES categories. Continuous variables were presented as mean (standard deviation, SD), and categorical variables were summarized as counts with percentages.

Multivariable linear regression models were used to examine the association between baseline SES and follow-up BAA, with the low SES group as the reference category. Beta coefficients (β) and 95% confidence intervals (CIs) were estimated. Model 1 was unadjusted. Model 2 was adjusted for CA (continuous), sex, ethnicity, marital status, urbanicity, and baseline BAA. Model 3 additionally included diet, and Model 4 additionally included LTPA based on Model 2. Model 5 was further adjusted for both diet and LTPA based on Model 2. Exploratory subgroup analyses were conducted by fitting linear regression models within strata defined by sex (men and women), age (<60 and ≥60 years), marital status (accompanied and unaccompanied), ethnicity (Han and minority), and urbanicity (rural and urban). Effect modification was additionally assessed by including interaction terms between SES and each subgroup variable in Model 2.

Mediation analysis under the counterfactual framework was conducted using the mediation package in R to evaluate the potential mediating roles of diet and LTPA [38]. The hypothesized relationships among SES, baseline BAA, the proposed mediators, follow-up BAA, and covariates are shown in the directed acyclic graph in Figure S4. In the primary analyses, we fitted separate mediation models for diet and LTPA and comparisons were performed for middle- versus low-SES and high- versus low-SES. For the mediator models, we used linear regression for the continuous aMED score and logistic regression for binary LTPA. For the outcome models, we fitted two separate linear regression models for follow-up BAA, each including SES and the corresponding mediator. Both the mediator and outcome models included the Model 2 covariates. We tested SES-by-mediator interactions in the outcome models and omitted the interaction terms from the primary models. We estimated the natural indirect effect (NIE), natural direct effect (NDE), total effect, and proportion mediated, and calculated percentile 95% CIs using 2000 nonparametric bootstrap resamples of the participants.

Several sensitivity analyses were performed to evaluate the robustness of the findings. First, we repeated the regression and mediation analyses with additional adjustment for the interval between baseline and follow-up assessments, modeled as a continuous variable. In the mediation analyses, interval was included only in the outcome models. Second, we repeated the mediation analyses using alternative definitions of diet and LTPA. For diet, we dichotomized the aMED score by comparing the upper two quintiles with the lower three. In addition, in a separate analysis, we used the modified DASH score in place of the aMED

score. For LTPA, we compared the highest tertile with the lower two tertiles [39]. Mediation analyses were then repeated using these alternative definitions. Third, we included aMED and LTPA in the same outcome model to estimate their joint indirect association with follow-up BAA. Fourth, additional adjustments were made for smoking status, drinking status, body mass index, insomnia, depression, anxiety and chronic diseases, including cancer, diabetes, cardiovascular disease, and chronic obstructive pulmonary disease. Both regression and mediation analyses were repeated.

All statistical analyses were performed using R (version 4.3.2). Two-sided p values < 0.05 were considered statistically significant.

3. Results

3.1. Characteristics of Study Population

Baseline characteristics of the participants according to SES groups are presented in Table 1. Among 9080 participants included in the longitudinal analysis, the mean age at baseline was 51.32 (10.75) years, 61.8% were women, 57.0% were of Han ethnicity, 89.3% were accompanied, and 67.3% were from rural areas. The mean BAA at baseline was −0.27 (5.79) years, and the mean follow-up BAA was 0.17 (6.13) years. Mean BAA was higher at follow-up than at baseline in all three SES groups, with the largest descriptive difference in the middle-SES group. In addition, both baseline and follow-up BAA differed across SES groups, with lower values observed in participants with higher SES ($p < 0.001$). Differences were also observed across SES groups for age, sex, ethnicity, marital status, urbanicity, diet and LTPA ($p < 0.001$).

Table 1. Baseline characteristics of the participants by socioeconomic status [a].

Characteristic	Total (n = 9080)	Low SES (n = 6388)	Middle SES (n = 1634)	High SES (n = 1058)	p [b]
CA, years	51.32 (10.75)	52.38 (10.09)	52.32 (11.79)	43.38 (9.62)	<0.001
Baseline BAA, years	−0.27 (5.79)	0.37 (5.74)	−1.47 (5.75)	−2.25 (5.46)	<0.001
Follow-up BAA, years	0.17 (6.13)	0.72 (6.02)	−0.73 (6.10)	−1.78 (6.28)	<0.001
Sex					<0.001
Male	3469 (38.2%)	2170 (34.0%)	789 (48.3%)	510 (48.2%)	
Female	5611 (61.8%)	4218 (66.0%)	845 (51.7%)	548 (51.8%)	
Ethnicity					<0.001
Han	5180 (57.0%)	2979 (46.6%)	1324 (81.0%)	877 (82.9%)	
Minority	3900 (43.0%)	3409 (53.4%)	310 (19.0%)	181 (17.1%)	
Marital status					<0.001
Accompanied	8111 (89.3%)	5654 (88.5%)	1485 (90.9%)	972 (91.9%)	
Unaccompanied	969 (10.7%)	734 (11.5%)	149 (9.1%)	86 (8.1%)	
Urbanicity					<0.001
Rural	6110 (67.3%)	5361 (83.9%)	573 (35.1%)	176 (16.6%)	
Urban	2970 (32.7%)	1027 (16.1%)	1061 (64.9%)	882 (83.4%)	
Diet [c]	24.87 (4.33)	24.30 (4.26)	26.18 (4.26)	26.28 (4.04)	<0.001
LTPA [d]					<0.001
Inactive	5699 (62.8%)	4485 (70.2%)	735 (45.0%)	479 (45.3%)	
Active	3381 (37.2%)	1903 (29.8%)	899 (55.0%)	579 (54.7%)	

[a] Data are presented as mean (SD) for continuous variables and count (percentage) for categorical variables. Data were complete for all variables. [b] The differences between categorical variables were assessed using $\chi 2$ tests, and the differences between continuous variables were assessed using one-way analysis of variance. [c] Diet was evaluated using the alternative Mediterranean diet (aMED) score. [d] LTPA was classified as active (≥7.5 MET-hours/week) or inactive (<7.5 MET-hours/week). Abbreviations: SES, socioeconomic status; BAA, biological age acceleration; CA, chronological age; LTPA, leisure-time physical activity.

3.2. Associations of SES with Follow-Up BAA

As shown in Table 2, higher SES was associated with lower follow-up BAA in Model 1. After adjustment for CA, sex, ethnicity, urbanicity, marital status, and baseline BAA (Model 2), the associations were attenuated but remained statistically significant ($p < 0.05$). Compared with participants with low SES, those with middle- and high-SES had lower BAA ($\beta = -0.45$, 95% CI: −0.75 to −0.14; $\beta = -0.91$, 95% CI: −1.29 to −0.53). Additional adjustment for diet and LTPA (Models 3–5) resulted in slight further attenuation. Both middle and high SES were associated with lower follow-up BAA compared with low SES across all models ($p < 0.05$ for each contrast).

Table 2. Associations of SES with follow-up BAA [a].

SES Class	Model 1	Model 2	Model 3	Model 4	Model 5
Low			Reference		
Middle	−1.45 (−1.78, −1.12)	−0.45 (−0.75, −0.14)	−0.38 (−0.68, −0.08)	−0.40 (−0.70, −0.10)	−0.35 (−0.65, −0.05)
High	−2.50 (−2.89, −2.10)	−0.91 (−1.29, −0.53)	−0.86 (−1.25, −0.48)	−0.86 (−1.24, −0.47)	−0.82 (−1.21, −0.44)

[a] Data are presented as β coefficients with 95% confidence intervals. Model 1 was unadjusted. Model 2 was adjusted for sex, age, ethnicity, urbanicity, marital status, and baseline BAA. Model 3 and Model 4 were additionally adjusted for diet and leisure-time physical activity, respectively. Model 5 was additionally adjusted for both diet and leisure-time physical activity. Abbreviations: SES, socioeconomic status; BAA, biological age acceleration.

In exploratory subgroup analyses based on Model 2, it was suggested that the association between SES and follow-up BAA differed by sex and ethnicity (both p for interaction < 0.05). For middle versus low SES, the estimates were numerically more negative in women and Han participants. For high versus low SES, the estimates were numerically more negative in men than in women, and the estimates were in opposite directions among Han participants (−1.07, 95% CI: −1.51 to −0.64) and ethnic minority participants (0.93, 95% CI: 0.04 to 1.82). Point estimates differed across age groups, marital status, and urbanicity subgroups, with little evidence of interaction (All p for interaction > 0.05). Details are presented in Supplementary Table S11.

3.3. Mediation Analyses of Diet and LTPA in the Association of SES with BAA

In the separate mediation models (Figure 2), the estimated indirect associations through diet were −0.06 (−0.10 to −0.04) for middle versus low SES and −0.05 (−0.08 to −0.02) for high versus low SES. The corresponding estimates through LTPA were −0.04 (−0.08 to −0.01) and −0.05 (−0.10 to −0.01). The estimated proportions were 14.2% (6.3% to 47.4%) and 5.2% (2.4% to 11.0%) for diet and 10.0% (2.5% to 34.9%) and 6.0% (1.4% to 13.5%) for LTPA, respectively. The SES-by-mediator interactions in the outcome models are not statistically significant ($p > 0.05$).

3.4. Sensitivity Analysis

In sensitivity analyses, the main findings remained relatively robust across most alternative specifications. When additional adjustment for the follow-up interval was added, the Model 2 estimates were −0.44 (−0.74 to −0.14) years for middle versus low SES and −0.89 (−1.27 to −0.50) for high versus low SES (Table S13). The indirect association did not materially change (Table S14). When mediation analyses were repeated using alternative categorizations of diet and LTPA, the overall patterns of mediation remained broadly similar (Table S15). When aMED and LTPA were included in the same outcome model, the estimated joint indirect associations with follow-up BAA were −0.09 (−0.14 to −0.05) for

middle versus low SES and −0.09 (−0.14 to −0.04) for high versus low SES (Table S16). After further adjustment for behavioral and health-related variables, the results were generally similar (Tables S17 and S18).

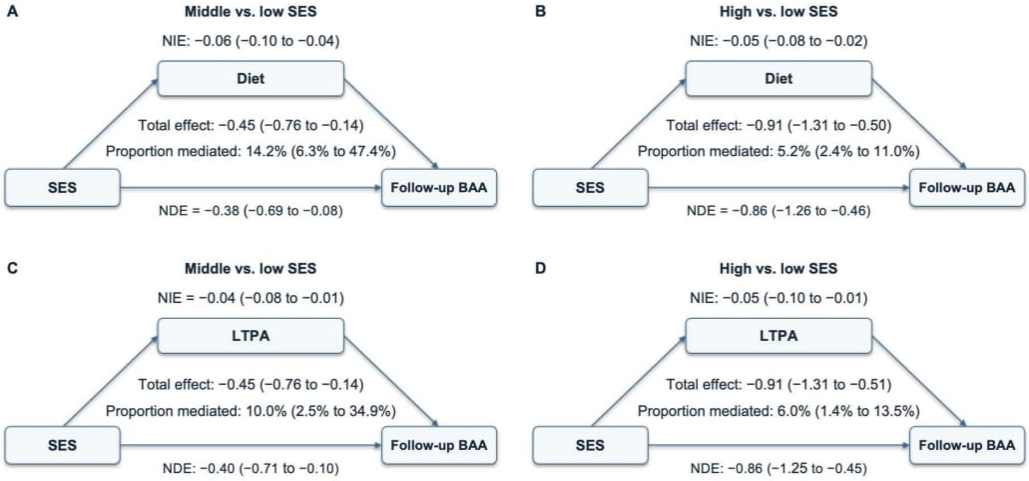

Figure 2. Mediation analysis of the association between SES and follow-up BAA. (**A**) Mediation analysis of diet for middle versus low SES. (**B**) Mediation analysis of diet for high versus low SES. (**C**) Mediation analysis of LTPA for middle versus low SES. (**D**) Mediation analysis of LTPA for high versus low SES. All mediation analyses were conducted under the counterfactual framework and adjusted for sex, age, ethnicity, urbanicity, marital status, and baseline BAA. Abbreviations: SES, socioeconomic status; LTPA, leisure-time physical activity; NIE, natural indirect effect; NDE, natural direct effect.

4. Discussion

In this longitudinal study of Chinese adults aged 30–79 years, higher SES was associated with lower follow-up BAA after accounting for baseline BAA and major sociodemographic characteristics. We further found that diet and LTPA each potentially mediated a modest proportion of this association.

Consistent with our findings, socioeconomic differences in BAA have been documented across diverse biological age metrics. Evidence based on clinically derived measures has shown that individuals in the highest poverty group had significantly greater age acceleration (AA) than those in the lowest poverty group, with coefficients of 0.96 for KDM acceleration [9]. Similar gradients have also been observed for DNA methylation-based measures. In the British cohort, participants in the least advantaged adult occupational class had 3.70 years greater GrimAge acceleration than those in the most advantaged class [10]. Likewise, in a Swiss population, adverse socioeconomic circumstances were associated with approximately 1.1–1.5 additional years of Levine's epigenetic age and GrimAge [11]. Comparable inverse associations between SES indicators and DunedinPACE have also been reported in German and multiethnic US populations [12,13]. Our findings extend this literature by providing longitudinal evidence that the inverse association between SES and BAA is not confined to Western populations or to cross-sectional settings. Follow-up BAA quantifies the difference between estimated BA and CA at the follow-up assessment. Even after adjustment for baseline BAA, the results should not be interpreted as differences in the rate of aging. In our study, both diet and LTPA may potentially account for a modest proportion of the association between SES and follow-up BAA. In the separate mediation analyses, the indirect estimates through diet and LTPA ranged from −0.06 to −0.04. The indirect association through diet accounted for 14.2% for middle versus low SES and 5.2% for high versus low SES, while the corresponding mediation proportions for LTPA were 10.0% and 6.0%, respectively. The findings for diet-related pathways are consistent with the limited

available evidence, although the magnitude of mediation varies across studies. An analysis based on the NHANES reported that the Dietary Inflammatory Index mediated 11.3% of the association [40], whereas findings from the Italian Moli-sani cohort suggested that the Mediterranean diet score accounted for approximately 2.7% to 6.2% of the association between socioeconomic trajectories and BAA [41]. By contrast, evidence regarding LTPA as a mediator has been more limited. To our knowledge, only one prior study has examined the mediating role of LTPA in the association between SES trajectories and BAA and reported no significant mediating effect [41]. Such variation in mediation may reflect differences in population context, the measurement of SES and mediators, and the BA metrics. Therefore, our findings warrant future validation from other studies.

Socioeconomic disadvantage is likely to influence BAA through multiple pathways [5]. In addition to diet and LTPA, psychosocial distress and adverse environmental exposures may also contribute to the biological embedding of socioeconomic disadvantage [42,43]. However, since diet and LTPA are largely modifiable, they may represent plausible, but partial, intervention targets to reduce socioeconomic inequalities in biological aging. Longitudinal studies with clearer temporal ordering could further evaluate these pathways and inform intervention trials testing whether improving diet or increasing LTPA helps reduce socioeconomic disparities in BAA and promote healthy aging.

This study has several strengths. First, SES was assessed at baseline, and the outcome was measured at follow-up, allowing us to examine their prospective association. Second, the analysis was conducted in a large population-based cohort from Southwest China, extending the evidence base beyond predominantly Western populations. Third, to our knowledge, this study is among the few studies to formally examine diet and LTPA as potential mediators in the association between SES and follow-up BAA. Fourth, BA was assessed using a KDM-based measure derived from routinely available clinical biomarkers, which may have greater relevance for routine health assessment. Finally, a range of sensitivity analyses yielded relatively consistent results, which supported the robustness of the findings.

Several limitations should be acknowledged. First, this was an observational study and residual confounding cannot be excluded. Unmeasured factors, such as healthcare utilization or medication use, may confound the SES–BAA, SES–mediator, and mediator–BAA associations. Exposure-induced mediator–outcome confounding is also possible. Although we adjusted for additional covariates to assess the robustness of the estimates, residual confounding still exists. Second, the temporal ordering of SES and the proposed mediators remains uncertain. The hypothesized pathways assume that longstanding socioeconomic circumstances may precede dietary and physical activity behaviors. However, in our study, SES, diet, and LTPA were assessed in the same baseline survey. Accordingly, the findings should be interpreted as evidence of potential behavioral pathways rather than definitive causal mediation. The indirect estimates were small, and estimated mediated proportions also had wide 95% CIs, indicating substantial uncertainty about the magnitude of these proportions. Third, SES and the mediators were derived from self-reported information, which may be subject to recall bias, reporting bias and investigator bias. However, these variables were collected using standardized questionnaires by well-trained investigators, which may help minimize such biases to some extent. In addition, SES measurement also involves uncertainty. Our LCA-derived classification was based on education, categorized annual household income, and occupation. Using more detailed income data, incorporating additional information such as wealth, or applying other statistical methods may yield different SES classifications and association estimates. Finally, the analytic sample was restricted to participants who completed both surveys and had complete data, which may have introduced some selection bias and limited generalizability. The analyses did not

account for clustering, stratification, or sampling weights, which may affect the estimated precision of the associations and how well the estimates reflect those in the target population. Taken together, these limitations should be considered when interpreting our findings.

5. Conclusions

In this prospective cohort of Chinese adults aged 30–79 years, higher SES was associated with lower follow-up BAA. Diet and LTPA emerged as potential behavioral pathways, with small estimated indirect associations. These findings suggest that supporting healthier diets and LTPA among socioeconomically disadvantaged groups may form part of broader efforts to address socioeconomic inequalities in biological aging. Future studies with clearer temporal sequence could further evaluate these potential pathways and inform the design of randomized controlled trials testing whether dietary or physical activity interventions can reduce socioeconomic disparities in BAA.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/healthcare14234096/s1, Text S1: Construction of KDM-BA and KDM-BA acceleration [22,24,25]; Text S2: Assessment of socioeconomic status using latent class analysis; Table S1: Baseline characteristics of included and excluded participants; Table S2: Variable-specific missing data among excluded participants; Table S3: Biomarker selection in the China Multi-Ethnic Cohort; Table S4: Correlation coefficients between candidate biomarkers in the China Multi-Ethnic Cohort; Table S5: Biomarker missingness among participants excluded because of unavailable BA; Table S6: Box–Cox transformation parameters for biomarkers; Table S7: Sex-specific parameters for estimating BA; Table S8: Associations of BAA with major chronic diseases in the CMEC; Table S9: Fit indices for latent class models; Table S10: Mean posterior probabilities, prevalence of latent classes, and item-response probabilities in models with three to five latent classes; Table S11: Subgroup analysis of the association between SES and follow-up BAA; Table S12: Distribution of follow-up interval; Table S13: Associations of SES with follow-up BAA additionally adjusted for follow-up interval; Table S14: Mediation analysis of the association between SES and follow-up BAA additionally adjusted for follow-up interval; Table S15: Mediation of the association between SES and follow-up BAA using alternative definitions of diet and LTPA; Table S16: Joint analysis of the association between SES and follow-up BAA; Table S17: Associations of SES with follow-up BAA additionally adjusting for behavioral and health-related variables; Table S18: Mediation of the association between SES and follow-up BAA additionally adjusting for behavioral and health-related variables; Figure S1: Bland–Altman plots for aging measures in the total population; Figure S2: Bland–Altman plots for aging measures in males; Figure S3: Bland–Altman plots for aging measures in females; Figure S4: Directed acyclic graph.

Author Contributions: Conceptualization: Z.Y. and J.Z. Data curation: J.Y. and J.Z. Formal analysis: Z.Y., J.Y., N.L., W.L., S.L., C.Y., J.C., Y.L. and Y.Z. Writing—original draft: Z.Y. and J.Y. Writing—review and editing: Z.Y., J.Y., N.L., W.L., S.L., C.Y., J.C., Y.L., Y.Z. and J.Z. Supervision: J.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Science and Technology Plan Projects of Tibet Autonomous Region, Grant No. XZ202301ZY0047G, and Key Collaborative Innovation Project of Zigong Academy of Medical Sciences, Grant No. 2025YJYZ0205.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Medical Ethics Review Committee of Sichuan University (protocol code K2016038, K2020022, 9 November 2016, 31 July 2020).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data are not publicly available due to privacy and ethical restrictions. The data may be obtained from the corresponding author upon reasonable request.

Acknowledgments: We thank all the participants and team members involved in the CMEC study for their contributions.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

SES	Socioeconomic status
BA	Biological age
BAA	Biological age acceleration
LTPA	Leisure-time physical activity

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