

Intrinsic capacity, domain-specific contributions, and longitudinal changes in relation to incident edentulism among middle-aged and older adults: a CHARLS longitudinal cohort study

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Abstract

Background

Edentulism affects approximately 25% of adults aged 60 years and older worldwide and is associated with impaired masticatory function and accelerated functional decline. Intrinsic capacity (IC), a composite measure of functional reserve proposed within the World Health Organization's Integrated Care for Older People framework, has not been longitudinally examined in relation to incident edentulism in large, representative cohorts.

Methods

This prospective cohort study used data from the China Health and Retirement Longitudinal Study (CHARLS), including 8,381 adults aged ≥ 45 years who were free of edentulism at Wave 1 in 2011. Incident edentulism was ascertained through Wave 4 in 2018. Baseline IC was operationalized as a 0–6-point composite score across six domains: locomotion, vitality, hearing, vision, cognition, and psychological well-being. Cox proportional hazards models with covariate adjustment were used as the primary analysis and were complemented by domain-specific contribution analyses. Time-varying Cox models and Wave 3 landmark analyses were used to evaluate dynamic changes in IC. Multiple sensitivity and subgroup analyses were conducted to assess robustness.

Results

During follow-up, 1,074 participants (12.8%) developed incident edentulism. In fully adjusted models, each 1-point increase in baseline IC was associated with an 8.7% lower risk of incident edentulism (HR = 0.913; 95% CI: 0.867–0.961, $P < 0.001$). Participants in the high IC group had a 21.7% lower risk than those in the low IC group (HR = 0.783; 95% CI: 0.690–0.890, $P < 0.001$), with a significant monotonic dose–response trend (HR = 0.830; 95% CI: 0.750–0.918, $P < 0.001$). Among IC domains, vitality impairment showed the strongest independent association with incident edentulism (mutually adjusted HR = 1.665; 95% CI: 1.341–2.069, $P < 0.001$), followed by hearing impairment (HR = 1.202; 95% CI: 1.011–1.428, $P = 0.037$). Adding IC domains improved the 4-year time-dependent area under the curve from 0.587 to 0.605. Time-varying analyses showed that each 1-point increase in updated IC was associated with a 12.0% lower risk of incident edentulism (HR = 0.880; 95% CI: 0.829–0.933, $P < 0.001$), and participants with persistently low IC had a significantly elevated risk after Wave 4 (HR = 1.424; 95% CI: 1.034–1.962, $P = 0.030$). Sensitivity analyses across multiple model specifications yielded consistent results. Subgroup analyses identified significant effect modification by age group (P for interaction = 0.033), with the strongest association observed among participants aged 55–64 years ($P < 0.001$).

Conclusions

Lower IC, particularly deficits in vitality and hearing, independently predicted incident edentulism. Dynamic IC trajectories conferred additional risk beyond baseline assessment, supporting IC as an integrative marker for the early identification of individuals at elevated risk of severe oral health deterioration in aging populations.

Background

China has one of the world's largest and fastest-growing older populations, with adults aged 60 years and older now exceeding 280 million and accounting for more than 20% of the total population [1]. Among age-related oral conditions, edentulism, defined as the complete absence of natural teeth, represents the most severe stage of oral health deterioration [2]. It is estimated to affect approximately 25% of adults aged 60 years and older worldwide [3] and 8.7% of adults aged 65–74 years in China [4]. Beyond its oral implications, edentulism is associated with nutritional compromise, increased chronic disease burden, and overall functional decline, making it a clinically meaningful and robust endpoint for longitudinal studies of advanced oral aging [5, 6]. As population aging accelerates globally, identifying integrative and modifiable risk indicators beyond conventional disease-specific approaches has become increasingly urgent.

Previous epidemiological studies have primarily examined determinants of tooth loss and edentulism through discrete, disease-specific risk factors, including oral hygiene behaviors, smoking, periodontal disease, diabetes, and socioeconomic disadvantage [7]. Such fragmented frameworks largely treat oral health decline as an isolated process, disconnected from the broader trajectory of physiological and functional aging [8]. They may therefore fail to capture how cumulative decline across multiple physiological systems, rather than any single disease state, shapes vulnerability to severe oral health outcomes, offering limited guidance for identifying individuals at elevated risk regardless of any single factor [9].

Intrinsic capacity (IC), proposed by the World Health Organization within its Integrated Care for Older People framework, has emerged as a central construct for operationalizing healthy aging. IC reflects an individual's composite functional capacity across multiple domains, including locomotion, vitality, sensory abilities, cognition, and psychological well-being [10]. Unlike traditional disease-counting approaches, IC emphasizes functional reserve and adaptive capacity [11]. Lower IC indicates diminished overall functional reserve and may signal an elevated risk of subsequent adverse outcomes [12]. Examining the association between IC and edentulism may therefore facilitate a deeper understanding of oral health deterioration from the perspective of systemic functional decline rather than isolated oral pathology. Conceptually, distinct IC domains may influence tooth loss risk through different pathways. Diminished vitality, characterized by unintentional weight loss and reduced appetite, may compromise nutritional and salivary function [13]. Hearing and mobility impairments may limit access to routine dental care and self-management of oral hygiene [14], whereas cognitive and psychological decline may erode motivation and capacity for sustained oral self-care [15]. These hypothesized pathways suggest that IC domains may not contribute equally to edentulism risk. However, the relative importance of each domain remains largely unexplored in the oral health literature.

To date, evidence linking intrinsic capacity (IC) to oral health outcomes remains limited. Existing studies are predominantly cross-sectional, which precludes causal inference and leaves the temporal direction of the IC–edentulism association unresolved [16, 17]. Moreover, IC has generally been operationalized as a single

composite score, with limited attention to domain-specific effects [18]. Most studies fail to account for the dynamic nature of IC over time, potentially underestimating cumulative risk among individuals with persistently low functional capacity [12]. It remains unclear whether longitudinal changes in IC provide additional predictive information for edentulism risk beyond a single baseline measurement, and which specific domains and trajectories are most relevant in large, nationally representative longitudinal cohorts.

To address these gaps, this study used data from the China Health and Retirement Longitudinal Study (CHARLS), a nationally representative longitudinal cohort, to comprehensively examine the association between IC and incident edentulism among middle-aged and older adults. Specifically, this study aimed to: (1) assess the longitudinal association between baseline IC and incident edentulism during follow-up; (2) quantify the relative contributions of domain-specific IC impairments to edentulism risk; and (3) examine associations between time-varying IC and IC trajectory patterns across Waves 1–3 (W1–W3) and incident edentulism after Wave 4 (W4). By integrating baseline, domain-specific, and longitudinal perspectives, this study provides evidence on IC as an integrative marker for identifying individuals at elevated risk of edentulism, with implications for targeted prevention in aging populations.

Methods

Data Source and Study Design

Longitudinal data derived from the China Health and Retirement Longitudinal Study (CHARLS) formed the empirical foundation of this investigation. Recognized as China's pioneering nationally representative prospective cohort, CHARLS was specifically designed to monitor the health and socioeconomic trajectories of middle-aged and older adults over time. A core objective of this project is the construction of a high-quality, publicly accessible micro-database on the aging population, encompassing a broad spectrum of variables ranging from economic circumstances to physical and mental health status. The national baseline survey was launched in 2011, with participants recruited across 150 county-level administrative units and 450 village-level communities, ultimately enrolling approximately 17,000 individuals from around 10,000 households. Enrolled participants undergo follow-up assessments at intervals of two to three years, supplemented by an additional survey conducted one year after the initial investigation. Comprehensive descriptions of the sampling framework and methodological procedures have been thoroughly documented in previously published literature [19]. The first wave of data collection (Wave 1, 2011) constituted the study baseline, while subsequent longitudinal observations were drawn from Wave 2 (2013), Wave 3 (2015), and Wave 4 (2018).

In the primary analysis, Wave 1 (W1) was used to define baseline intrinsic capacity (IC), dental status, and covariates. Waves 2–4 (W2–W4) were used to ascertain incident edentulism during follow-up. Repeated IC measurements from W1 to W3 were used in time-varying Cox proportional hazards models and W3 landmark analyses to evaluate dynamic changes in IC.

Study Population: Inclusion and Exclusion Criteria

Participants were eligible for inclusion if they were aged 45 years or older at W1, had a valid unique identification number, available baseline age information, baseline dental and denture status information, baseline IC score, and at least one valid follow-up assessment of edentulism. Individuals reporting edentulism or a proxy indicator of severe tooth loss at baseline were excluded to ensure that all included participants were at risk of developing incident edentulism.

The study population was derived as follows: 17,596 individuals were initially identified. 165 individuals were excluded because of missing age information, and 600 were excluded because they were younger than 45 years. A further 25 individuals were excluded because of missing baseline dental or denture status. After excluding 1,486 individuals with baseline edentulism or proxy severe tooth loss, 15,320 participants remained. Of these, 6,579 were excluded because of missing baseline IC data, leaving 8,741 participants. Finally, 360 participants without any valid follow-up assessment of edentulism were excluded, resulting in a final analytic cohort of 8,381 participants (Fig. 1).

Exposure Variable: Intrinsic Capacity Score

The primary exposure was the baseline intrinsic capacity (IC) score measured at Wave 1 (W1). IC was operationalized as a 0–6-point scale, with higher scores indicating better intrinsic capacity. The score was constructed from six binary screening indicators within six core domains of the healthy aging framework: locomotor function, vitality, sensory capacity (hearing and vision), cognition, and psychological well-being [20].

(1) Locomotor function: Locomotor function was assessed using the five-time sit-to-stand test. Performance was classified as preserved if the task was completed independently within 14 seconds. Otherwise, it was classified as impaired.

(2) Vitality: Vitality was assessed using body mass index (BMI). BMI values $> 18.5 \text{ kg/m}^2$ were classified as preserved, whereas BMI values $\leq 18.5 \text{ kg/m}^2$ were classified as impaired. Implausible extreme BMI values were treated as missing during data cleaning.

(3) Hearing: Self-reported hearing rated as “poor” was classified as impaired. All other responses were classified as preserved.

(4) Vision: Participants reporting neither farsightedness nor nearsightedness as “poor” were classified as having preserved vision. Participants reporting either farsightedness or nearsightedness as “poor” were classified as impaired.

(5) Cognition: Cognition was assessed using a composite of memory and mental status indicators. Participants whose memory and mental status scores were both no lower than the wave-specific mean minus one standard deviation were classified as preserved. Otherwise, they were classified as impaired.

(6) Psychological well-being: Psychological well-being was assessed using the 10-item Center for Epidemiologic Studies Depression Scale (CES-D-10). Scores < 12 were classified as preserved, whereas scores ≥ 12 were classified as impaired.

In addition to the continuous IC score, baseline IC was categorized as low IC (0–4 points) or high IC (5–6 points) for cumulative incidence analyses and binary Cox regression models [21]. To assess dose–response relationships, IC was further grouped into three categories: 0–2, 3–4, and 5–6 points [22].

Outcome Variable: Incident Edentulism

The outcome was incident edentulism during follow-up. Baseline dental and denture status variables were used to exclude participants with edentulism or proxy indicators of severe tooth loss at baseline. Participants who first reported edentulism during Waves 2–4 (W2–W4) were defined as incident cases. Follow-up time was calculated from the date of the Wave 1 interview to the earliest occurrence of incident edentulism, last valid dental assessment, death, or loss to follow-up, whichever occurred first. Death and loss to follow-up were treated as censoring events.

Covariates

Covariates included in the main adjusted models were sex, educational attainment, marital status, household wealth quartiles, urban–rural residence, smoking history, alcohol consumption history, hypertension, and diabetes [23, 24]. Age, a key determinant of edentulism risk, was handled through stratification in the primary Cox models rather than as a standard linear covariate [25]. Age was categorized as 45–54, 55–64, 65–74, and ≥ 75 years.

The age-stratified Cox model allowed baseline hazard functions to vary across age strata, providing a flexible approach to accounting for the strong age dependence of edentulism. To evaluate the robustness of age specification, sensitivity analyses additionally modeled age as a continuous variable, modeled age using natural splines, and applied alternative age-stratification schemes.

Statistical Analysis

Baseline characteristics were summarized according to incident edentulism status. Continuous variables are presented as means and standard deviations, and categorical variables are presented as frequencies and percentages. Between-group differences were assessed using t-tests or chi-square tests, as appropriate.

The primary analysis used Cox proportional hazards regression models to evaluate the association between baseline IC and incident edentulism. Model 1 was unadjusted. Model 2 was stratified by age group and adjusted for sex. Model 3 was additionally adjusted for educational attainment, marital status, household wealth, and urban–rural residence. Model 4 was further adjusted for smoking status, alcohol consumption, hypertension, and diabetes.

Cumulative incidence curves were estimated using the 1 – Kaplan–Meier method to compare edentulism risk between low and high IC groups, with differences assessed using the log-rank test. Dose–response relationships were examined using restricted cubic spline models, and tests were performed for both the overall association and nonlinearity. The proportional hazards assumption was evaluated using Schoenfeld residuals.

Domain-specific contribution analyses were conducted at two levels. First, each of the six IC domain impairments was entered separately into Cox models. Second, all six domains were simultaneously included in mutually adjusted models to assess their independent associations with edentulism risk. The incremental predictive performance of IC was further evaluated by comparing the C-index and time-dependent area under the curve across three models: the base model, the base model plus total IC score, and the base model plus IC domain indicators. Permutation importance derived from random survival forests was used to quantify the relative predictive contribution of each IC domain.

Dynamic analyses included time-varying Cox proportional hazards models and W3 landmark analyses. For the time-varying models, person–interval data structures were constructed for W1–W2, W2–W3, and W3–W4, with updated IC values at the start of each interval used as time-varying exposures. Standard errors were estimated using cluster-robust variance at the participant level. The W3 landmark analysis examined baseline and change metrics, including mean IC from W1 to W3, change in IC from W1 to W3, and IC change categories, to predict incident edentulism during W3–W4.

Sensitivity analyses included alternative age specifications, exclusion of early events occurring at W2, use of reconstructed domain-sum IC scores, multiple imputation for missing data, and Fine–Gray competing risk models treating death as a competing event. Subgroup analyses were conducted by sex, age group, educational attainment, marital status, wealth level, urban–rural residence, smoking status, alcohol consumption, hypertension, and diabetes. Interaction effects were assessed using likelihood ratio tests.

Results

Study Population and Baseline Characteristics

Among the 8,381 participants included in the final baseline analytic cohort, 1,074 (12.8%) developed incident edentulism during follow-up. The derivation of the analytic sample from the original CHARLS Wave 1 cohort is summarized in the participant flow diagram (Fig. 1). Compared with participants who remained free of edentulism, those who developed incident edentulism were older at baseline (mean age, 62.06 vs. 56.56 years) and were overrepresented in the oldest age strata. The incident-edentulism group also had a less favorable sociodemographic profile, including higher proportions of participants with low educational attainment, unmarried or otherwise unpartnered status, and rural residence. All between-group differences were statistically significant ($P < 0.001$) (Table 1).

With respect to intrinsic capacity, participants who subsequently developed edentulism had a lower mean baseline IC score than those who did not (4.54 vs. 4.90 points), and a substantially higher proportion were classified as having low IC (44% vs. 31%). At the domain level, impairment was more prevalent among incident cases across all six IC domains, with the largest relative differences observed for vitality and hearing impairment (Table 1).

Table 1
Baseline characteristics of participants according to incident edentulism status

Characteristics	Overall N = 8,381	No incident edentulism N = 7,307	Incident edentulism N = 1,074	p-value
Age, years	57.26 (8.39)	56.56 (8.13)	62.06 (8.57)	< 0.001
Age group				< 0.001
45–54	3,434 (41%)	3,242 (44%)	192 (18%)	
55–64	3,322 (40%)	2,842 (39%)	480 (45%)	
65–74	1,345 (16%)	1,033 (14%)	312 (29%)	
>=75	280 (3.3%)	190 (2.6%)	90 (8.4%)	
Sex				0.5
Male	4,346 (52%)	3,801 (52%)	545 (51%)	
Female	4,035 (48%)	3,506 (48%)	529 (49%)	
Education				< 0.001
Low	7,295 (87%)	6,283 (86%)	1,012 (94%)	
Middle	950 (11%)	895 (12%)	55 (5.1%)	
High	136 (1.6%)	129 (1.8%)	7 (0.7%)	
Marital status				< 0.001
Married/Partnered	7,585 (91%)	6,672 (91%)	913 (85%)	
Unmarried/Other	796 (9.5%)	635 (8.7%)	161 (15%)	
Household wealth quartile				< 0.001
Q1 (Lowest)	1,422 (17%)	1,192 (16%)	230 (21%)	
Q2	1,569 (19%)	1,358 (19%)	211 (20%)	
Q3	1,723 (21%)	1,513 (21%)	210 (20%)	
Q4 (Highest)	1,599 (19%)	1,430 (20%)	169 (16%)	
Missing	2,068 (25%)	1,814 (25%)	254 (24%)	
Residence				< 0.001
Urban	3,304 (39%)	2,957 (40%)	347 (32%)	

Characteristics	Overall N = 8,381	No incident edentulism N = 7,307	Incident edentulism N = 1,074	p-value
Rural	5,077 (61%)	4,350 (60%)	727 (68%)	
Ever smoking	3,518 (42%)	3,045 (42%)	473 (44%)	0.2
Ever drinking	3,515 (42%)	3,088 (42%)	427 (40%)	0.13
Missing	3	3	0	
Hypertension	2,083 (25%)	1,794 (25%)	289 (27%)	0.10
Missing	39	33	6	
Diabetes	505 (6.1%)	443 (6.1%)	62 (5.8%)	0.7
Missing	70	63	7	
Baseline IC score	4.85 (1.14)	4.90 (1.12)	4.54 (1.25)	< 0.001
Baseline IC category				< 0.001
Low IC (0–4)	2,756 (33%)	2,280 (31%)	476 (44%)	
High IC (5–6)	5,625 (67%)	5,027 (69%)	598 (56%)	
Locomotion impairment				< 0.001
Preserved	7,323 (87%)	6,446 (88%)	877 (82%)	
Impaired	1,058 (13%)	861 (12%)	197 (18%)	
Vitality impairment				< 0.001
Preserved	7,982 (95%)	7,003 (96%)	979 (91%)	
Impaired	388 (4.6%)	294 (4.0%)	94 (8.8%)	
Missing	11	10	1	
Hearing impairment				< 0.001
Preserved	7,475 (89%)	6,569 (90%)	906 (84%)	
Impaired	906 (11%)	738 (10%)	168 (16%)	
Vision impairment				0.002
Preserved	5,716 (68%)	5,029 (69%)	687 (64%)	
Impaired	2,665 (32%)	2,278 (31%)	387 (36%)	
Cognition impairment				< 0.001

Characteristics	Overall N = 8,381	No incident edentulism N = 7,307	Incident edentulism N = 1,074	p-value
Preserved	6,664 (80%)	5,890 (81%)	774 (72%)	0.016
Impaired	1,717 (20%)	1,417 (19%)	300 (28%)	
Psychological impairment				
Preserved	6,405 (76%)	5,616 (77%)	789 (73%)	
Impaired	1,976 (24%)	1,691 (23%)	285 (27%)	

Values are presented as mean (SD) for continuous variables and n (%) for categorical variables. IC, intrinsic capacity. Baseline edentulism/severe tooth loss was defined using the CHARLS Wave 1 tooth/denture-related item. P values were calculated using t tests or chi-square tests as appropriate.

Baseline IC and Risk of Incident Edentulism

Baseline IC showed a consistent inverse association with the risk of incident edentulism across all stages of model adjustment. Although the association was attenuated after adjustment, it remained statistically significant. In the fully adjusted model, each 1-point increase in IC was associated with an 8.7% lower risk of incident edentulism (HR = 0.913; 95% CI: 0.867–0.961, $P < 0.001$) (Table 2).

Consistent findings were observed in categorical analyses. Compared with participants in the low IC group, those in the high IC group had a 21.7% lower risk of incident edentulism (HR = 0.783; 95% CI: 0.690–0.890, $P < 0.001$). When IC was further divided into three ordinal categories, the risk decreased monotonically with increasing IC level, and the trend test across categories was statistically significant (HR = 0.830; 95% CI: 0.750–0.918, $P < 0.001$). Cumulative incidence curves showed that participants in the low IC group had a consistently higher cumulative incidence of edentulism during follow-up than those in the high IC group, with a statistically significant between-group difference (log-rank test, $P < 0.0001$) (Fig. 2).

Dose–response analysis showed a significant overall association between IC and incident edentulism risk (P -overall = 0.001). However, there was no statistically significant evidence of nonlinearity (P -nonlinear = 0.109) (Fig. 3).

Table 2
Association between baseline intrinsic capacity and incident edentulism

Exposure	Model	N	Events	HR (95% CI)	P value
Baseline IC score, per 1-point increase	Model 1 (Crude)	8,381	1,074	0.796 (0.759–0.834)	< 0.001
Baseline IC score, per 1-point increase	Model 2 (Age strata + sex)	8,381	1,074	0.883 (0.841–0.928)	< 0.001
Baseline IC score, per 1-point increase	Model 3 (+ socioeconomic factors)	8,381	1,074	0.917 (0.871–0.965)	< 0.001
Baseline IC score, per 1-point increase	Model 4 (Fully adjusted)	8,282	1,064	0.913 (0.867–0.961)	< 0.001
High IC (5–6) vs Low IC (0–4)	Model 4 (Fully adjusted)	8,282	1,064	0.783 (0.690–0.890)	< 0.001
IC category 3–4	Model 4 (Fully adjusted)	8,282	1,064	0.951 (0.737–1.226)	0.697
IC category 5–6	Model 4 (Fully adjusted)	8,282	1,064	0.750 (0.581–0.967)	0.027
P for trend across IC categories	Model 4 (Fully adjusted)	8,282	1,064	0.830 (0.750–0.918)	< 0.001

Model 1: crude model. Model 2: stratified by age group and adjusted for sex. Model 3: additionally adjusted for education, marital status, household wealth, and rural residence. Model 4: additionally adjusted for smoking, drinking, hypertension, and diabetes. Age group was included as a stratification factor in Cox models; therefore, no HR for age is reported.

Domain-Specific IC Impairments and Risk of Incident Edentulism

To identify which components of intrinsic capacity contributed most strongly to edentulism risk, we examined the six IC domains individually and then in a mutually adjusted model that included all six domains simultaneously (Table 3, Fig. 4). Vitality impairment, although the least prevalent domain impairment (4.6%), was associated with the highest absolute event rate among impaired participants (24.2%) and showed the strongest association with incident edentulism. In the single-domain model, vitality impairment was associated with a 64.7% higher risk of incident edentulism (HR = 1.647; 95% CI: 1.327–2.044, $P < 0.001$). This association remained essentially unchanged after mutual adjustment for the other five domains (HR = 1.665; 95% CI: 1.341–2.069, $P < 0.001$), indicating that the vitality–edentulism association was not explained by co-occurring impairment in other IC domains.

Hearing impairment showed the second-strongest and independently significant association with incident edentulism, with a 22.0% increased risk in the single-domain model and a 20.2% increased risk in the mutually adjusted model (HR = 1.202; 95% CI: 1.011–1.428, $P = 0.037$). Locomotion impairment was

associated with elevated risk in the single-domain model (HR = 1.180; 95% CI:1.005–1.385, $P = 0.043$), but the association was attenuated to borderline significance after mutual adjustment (HR = 1.172; 95% CI:0.997–1.377, $P = 0.054$), suggesting partial confounding or shared variance with other IC domains, particularly vitality and hearing. In contrast, vision, cognition, and psychological well-being impairments were not independently associated with incident edentulism in the mutually adjusted model ($P > 0.05$) (Table 3, Fig. 4). Overall, these domain-level findings indicate that the IC–edentulism association is primarily driven by deficits in vitality and, to a lesser extent, hearing, rather than being uniformly distributed across all domains of intrinsic capacity.

Table 3
Domain-specific associations of intrinsic capacity impairments with incident edentulism

Domain	Impaired N	Impaired %	Events in impaired	Event rate in impaired	Separate model HR (95% CI)	P	Mutual model HR (95% CI)	P
Locomotion impairment	1,058	12.6%	197	18.6%	1.180 (1.005–1.385)	0.043	1.172 (0.997–1.377)	0.054
Vitality impairment	388	4.6%	94	24.2%	1.647 (1.327–2.044)	< 0.001	1.665 (1.341–2.069)	< 0.001
Hearing impairment	906	10.8%	168	18.5%	1.219 (1.030–1.442)	0.021	1.202 (1.011–1.428)	0.037
Vision impairment	2,665	31.8%	387	14.5%	1.073 (0.945–1.218)	0.276	1.038 (0.910–1.184)	0.577
Cognition impairment	1,717	20.5%	300	17.5%	1.121 (0.974–1.291)	0.110	1.083 (0.940–1.248)	0.271
Psychological impairment	1,976	23.6%	285	14.4%	1.012 (0.879–1.165)	0.866	0.944 (0.816–1.091)	0.434

Each domain impairment was coded as impaired versus preserved. Separate-domain models included one IC domain at a time. The mutually adjusted model included all six IC domains simultaneously. All models were stratified by age group and adjusted for sex, education, marital status, household wealth, rural residence, smoking, drinking, hypertension, and diabetes.

Predictive Contribution of IC Domains

In terms of predictive performance, the C-index of the baseline covariate model was 0.570. After adding the total IC score, the C-index increased to 0.578 (Δ C-index = 0.008). When IC domain indicators were substituted for the total IC score, the C-index increased to 0.583 (Δ C-index = 0.013 relative to the base

model). The 4-year time-dependent AUC increased from 0.587 to 0.605 ($\Delta\text{AUC} = 0.019$) (Table 4). The corresponding improvement in the 7-year AUC was more modest.

These findings suggest that IC and its domains provided a modest incremental improvement in predictive performance beyond traditional covariates, although the overall gain in discrimination was limited. Permutation importance from random survival forest models indicated that vitality impairment had the highest relative predictive importance among the IC domains (Fig. 5). These results should be interpreted as reflecting predictive contributions rather than causal effects. Accordingly, machine learning metrics should be considered complementary to Cox regression effect estimates, rather than substitutes for them.

Table 4
Incremental predictive value of intrinsic capacity domains for incident edentulism

Model	C-index	SE	AUC at 4 years	AUC at 7 years	$\Delta\text{C-index}$	$\Delta\text{AUC at 4 years}$	$\Delta\text{AUC at 7 years}$
Base model	0.570	0.01	0.587	0.566	0.000	0.000	0.000
Base + total IC	0.578	0.01	0.596	0.572	0.008	0.009	0.006
Base + IC domains	0.583	0.01	0.605	0.571	0.013	0.019	0.006

C-index and time-dependent AUC were estimated in complete cases for the variables included in the prediction models. Delta values were calculated relative to the base model.

Dynamic IC and Risk of Incident Edentulism After Wave 4

Because intrinsic capacity is a dynamic construct that may change during aging, we further examined whether repeated IC measurements during follow-up, rather than baseline IC alone, were associated with subsequent edentulism risk (Table 5, Fig. 6). Time-varying Cox regression analyses showed that updated IC levels during follow-up were significantly associated with incident edentulism. Each 1-point increase in time-updated IC was associated with a 12.0% lower risk of incident edentulism ($\text{HR} = 0.880$; 95% CI:0.829–0.933, $P < 0.001$). The hazard ratio for dynamic high IC versus dynamic low IC was 0.752. These findings indicate that baseline IC is predictive of edentulism risk and that maintaining higher IC levels during follow-up is also associated with a lower risk of incident edentulism (Table 5).

The W3 landmark analysis further showed that changes in IC between W1 and W3 were associated with the risk of incident edentulism after W4. Each 1-point increase in IC score from W1 to W3 was associated with a 10.2% lower risk of subsequent edentulism ($\text{HR} = 0.898$; 95% CI:0.811–0.994, $P = 0.037$). Participants in the stable low IC group had a significantly higher risk of incident edentulism after W4 ($\text{HR} = 1.424$; 95% CI:1.034–1.962, $P = 0.030$) (Table 5, Fig. 6). Analyses based on mean IC from W1 to W3, rather than the W1-to-W3 change, showed a consistent direction of association, although the result did not reach conventional statistical significance ($P = 0.069$).

Table 5
Longitudinal intrinsic capacity measures and risk of incident edentulism

Exposure	model	N	Units	Events	HR (95% CI)	P value
Time-varying IC score	Time-varying Cox	7,922	16,603	814	0.880 (0.829–0.933)	< 0.001
Time-varying High IC vs Low IC	Time-varying Cox	7,922	16,603	814	0.752 (0.651–0.870)	< 0.001
Mean IC from Waves 1–3	W3 landmark	5,299	5,299	304	0.890 (0.785–1.009)	0.069
Change in IC from Wave 1 to Wave 3	W3 landmark	4,510	4,510	262	0.898 (0.811–0.994)	0.037
IC change group: Improving	W3 landmark	4,510	4,510	262	0.964 (0.666–1.395)	0.846
IC change group: Declining	W3 landmark	4,510	4,510	262	1.078 (0.737–1.576)	0.699
IC change group: Stable low	W3 landmark	4,510	4,510	262	1.424 (1.034–1.962)	0.030

Time-varying models used updated IC scores at the beginning of each follow-up interval. Robust standard errors were estimated using participant-level clustering. Landmark models used Wave 1–3 IC information to predict Wave 4 incident edentulism.

Proportional Hazards Assumption and Sensitivity Analyses

Schoenfeld residual tests indicated no violations of the proportional hazards assumption for the primary exposure or the overall model, supporting the appropriateness of the Cox proportional hazards framework for the primary analyses (**Table S1, Fig. S1**).

We conducted a series of sensitivity analyses to evaluate the robustness of the association between baseline IC and incident edentulism under alternative analytic specifications (**Table S2**). Overall, the sensitivity analyses supported the robustness of the main findings. Associations were consistent in direction and magnitude across multiple specifications, including age modeled as a continuous variable ($P = 0.002$), age modeled using natural splines ($P = 0.002$), alternative age-stratification schemes ($P < 0.001$), exclusion of early events at Wave 2 ($P = 0.014$), use of reconstructed domain-sum IC scores ($P < 0.001$), multiple imputation for missing data ($P = 0.001$), and competing risk models ($P = 0.001$). In the competing risk model treating death as a competing event, each 1-point increase in IC was associated with a hazard ratio of 0.918, suggesting that competing mortality risk was unlikely to explain the primary association between IC and incident edentulism.

Subgroup Analyses

We examined whether the association between baseline IC and incident edentulism was consistent across clinically and demographically relevant subgroups (**Table S3, Fig. S2**). A statistically significant interaction

was observed for age group (P for interaction = 0.033), indicating heterogeneity in the strength of the IC–edentulism association across age strata. The association was strongest among participants aged 55–64 years ($P < 0.001$), whereas it did not reach statistical significance in the youngest age group (45–54 years; $P = 0.399$) or the oldest age group (≥ 75 years; $P = 0.171$). The interaction for smoking status was borderline significant (P for interaction = 0.059), whereas no statistically significant interactions were observed for other subgroups (P for interaction > 0.05). Given differences in sample size and event numbers across strata, these subgroup findings should be interpreted as exploratory.

Unadjusted Event Rates Across IC Change Groups

As a descriptive supplement to the dynamic analyses, the stable low group had the highest unadjusted event rate of incident edentulism during Waves 3–4 (64/636), whereas the stable high group had an event rate of 125/2,665 (**Fig. S3**). This pattern of unadjusted event rates was consistent with the direction of the adjusted hazard ratio results.

Discussion

This study used nationally representative longitudinal data from CHARLS to systematically examine the association between intrinsic capacity (IC) and incident edentulism among middle-aged and older adults. Existing evidence on the association between IC and oral health has been predominantly cross-sectional. A clinic-based study found that a greater number of IC deficits was associated with an increased risk of oral hypofunction in hospitalized older patients [26]. However, cross-sectional designs cannot establish the temporal direction of the association, including whether IC decline precedes or follows tooth loss. By ascertaining incident edentulism across three follow-up waves among participants free of edentulism at baseline, our prospective design establishes a clearer temporal sequence than is possible in cross-sectional studies.

The magnitude of the baseline IC–edentulism association is informative when considered alongside the broader IC outcomes literature. A systematic review and meta-analysis of 37 longitudinal studies reported a pooled hazard ratio of 0.57 for the association between IC and all-cause mortality [12]. The more conservative estimate observed in the present study (HR = 0.913 per 1-point increase) is expected, given that edentulism is a multifactorial outcome that may be partially mitigated through dental care and clinical intervention [27]. Nevertheless, this independent, linear, and statistically significant association over seven years of follow-up in a large nationally representative cohort has substantive public health implications. It also extends the IC functional aging framework, previously validated primarily against mortality and disability endpoints, to severe oral health deterioration, a dimension largely absent from the existing IC evidence base.

Among the six IC domains, vitality impairment, operationalized as unintentional weight loss and reduced appetite, showed the strongest and most robust independent association with incident edentulism (mutually adjusted HR = 1.665). This association remained essentially unchanged after mutual adjustment, suggesting independence from concurrent impairments in other IC domains. Two biological pathways may explain this domain-specific association. First, protein-energy malnutrition may contribute to salivary gland atrophy and reduced antimicrobial defense, thereby compromising oral ecological resistance to acidogenic bacteria and accelerating caries progression[28]. A systematic review which synthesized evidence from ten cross-

sectional studies, reported consistent associations between malnutrition and reduced tooth count, lower salivary flow, and increased risk of periodontal pathology in older populations [29]. Second, reduced body weight may be associated with lower mandibular bone mineral density, providing a metabolic mechanism through which vitality deficits may facilitate alveolar bone resorption and tooth loss [30]. The bidirectional relationship between nutritional status and oral health further supports this upstream pathway [31]. Hearing impairment showed the second-strongest independently significant association with incident edentulism (mutually adjusted HR = 1.202). In contrast to vitality, the plausible mechanism may operate primarily through behavioral and healthcare-access pathways rather than direct physiological processes. An analysis of Survey found that older adults with sensory limitations had significantly higher odds of delayed or forgone dental care than those without disability [32], providing empirical support for a mechanism in which hearing loss may create communication barriers and care-seeking avoidance that restrict access to preventive dental services [33]. The borderline-significant association observed for locomotion impairment ($P = 0.054$) is directionally consistent with this hypothesis and suggests that dental visit frequency may be an important mediating factor warranting further investigation [34].

Beyond baseline IC levels, the time-varying and landmark analyses indicate that IC is better conceptualized as a dynamic marker of functional reserve rather than a static exposure. Updated IC levels during follow-up were significantly associated with edentulism risk, and improvement in IC between Wave 1 and Wave 3 was associated with a lower risk of post-Wave 4 edentulism. In contrast, the stable low IC group exhibited the highest adjusted hazard. Collectively, these findings suggest that sustained low functional reserve, rather than a single low-IC measurement, may represent the most clinically relevant pattern of vulnerability for severe oral health deterioration.

The IC–edentulism associations observed in this study may be interpreted through two complementary mechanistic frameworks. At the biological level, inflammaging, characterized by a chronic, low-grade systemic inflammatory state associated with aging [35], may contribute to sustained periodontal tissue destruction through persistent pro-inflammatory signaling [36]. Reduced vitality and muscle mass may share underlying physiological substrates with this inflammatory milieu, potentially amplifying alveolar bone resorption [37]. At the behavioral level, functional decline may contribute to oral health deterioration by impairing oral self-care, limiting access to dental services, and worsening masticatory and nutritional function [38, 39].

The subgroup analysis identified statistically significant effect modification by age group (P for interaction = 0.033), with the strongest protective association observed among participants aged 55–64 years. No significant associations were detected in the youngest (45–54 years) or oldest (≥ 75 years) strata. This pattern may reflect the relative infrequency of edentulism-relevant IC impairment in younger adults and the predominance of irreversible structural oral tissue loss in the oldest adults [5]. These findings suggest that ages 55–64 years may represent a meaningful window during which functional reserve remains available and IC deficits may still be modifiable before advanced oral deterioration occurs. At the implementation level, the WHO ICOPE five-step clinical pathway has demonstrated feasibility in primary care settings, and the present findings provide longitudinal empirical support for embedding oral health assessment within this pathway [40]. Because vitality and hearing are directly evaluated ICOPE domains, their independent associations with incident edentulism add a clinically interpretable oral health prognostic dimension to

standard ICOPE screening results [41]. This supports coordinated oral health referral within ICOPE screening workflows. The modest but consistent improvement in AUC ($\Delta\text{AUC} = 0.019$) suggests potential value for population-level risk stratification when IC is already embedded in routine assessments.

Several limitations of this study should be considered. First, edentulism status was ascertained by self-report without clinical dental examination, which may have introduced misclassification and precluded differentiation of tooth loss etiology, including caries, periodontal disease, trauma, and elective extraction. Second, IC was operationalized using available CHARLS questionnaire items, which may not correspond precisely to standardized WHO ICOPE assessment instruments, limiting direct comparability with other studies. Third, the absence of dental utilization data and oral hygiene behavior records precluded formal mediation analysis of physiological and behavioral pathways, which remains a methodological priority for future research. Finally, although the prospective design strengthens temporal inference, reverse causality cannot be fully excluded. Early oral functional limitations may influence dietary intake and thereby affect vitality scores. Future research should replicate these findings in cohorts with standardized clinical oral examinations, incorporate dental utilization and behavioral variables to test pathway-specific mediation, and evaluate whether IC-enhancing interventions confer measurable benefits for oral health outcomes.

Conclusion

This prospective cohort study showed that lower intrinsic capacity independently predicted incident edentulism among middle-aged and older Chinese adults. Domain-specific analyses identified vitality and hearing deficits as the primary contributors to edentulism risk. Dynamic IC trajectories provided additional prognostic value beyond baseline assessment, with persistently low IC conferring significantly elevated risk, underscoring the importance of repeated functional evaluation. The association was most pronounced among participants aged 55–64 years, suggesting a critical window for intervention. These findings support integrating intrinsic capacity assessment into oral health risk stratification frameworks for aging populations, and highlight the potential of early, multidomain functional interventions in reducing the long-term burden of severe tooth loss.

Declarations

The online version contains supplementary material available at

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Authors contributions

Chengxi Li and Xue Wang: Data curation, Investigation, Conceptualization, Writing—original draft, Methodology. **Jiasu Li:** Formal Analysis, Software. **Yan Wang:** Validation, Visualization. **Weijian Song:** Conceptualization, Methodology, Supervision, Resources, Project administration, Writing – review & editing. All authors reviewed the manuscript.

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Data availability

The datasets generated and/or analysed during the current study are available in the CHARLS database (<http://charls.pku.edu.cn/>).

Ethics approval and consent to participate

This study was carried out based on data extracted from the CHARLS public database, and all methods were performed according to the relevant guidelines and regulations. Written informed consent was obtained from all participants or their legal agents before the commencement of any study process. The ethics approval for the collection of CHARLS data has been approved by the Peking University Biomedical Ethics Review Committee (IRB00001052-11015), and all procedures were performed in accordance with the 1964 Declaration of Helsinki and its later amendments or with comparable ethical standards.

Competing interests

The authors declare no competing interests.

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Figures

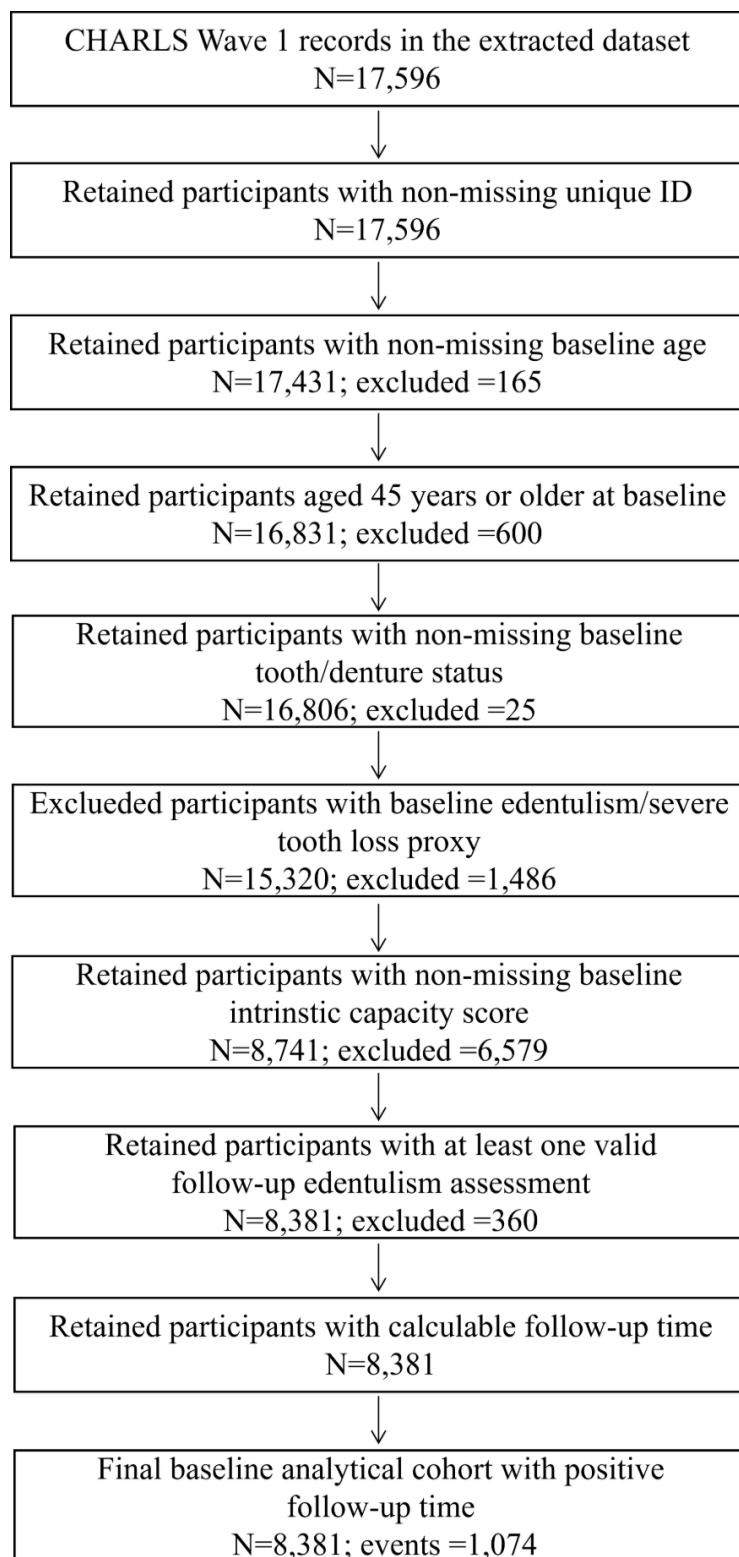


Figure 1

Participant selection flow chart

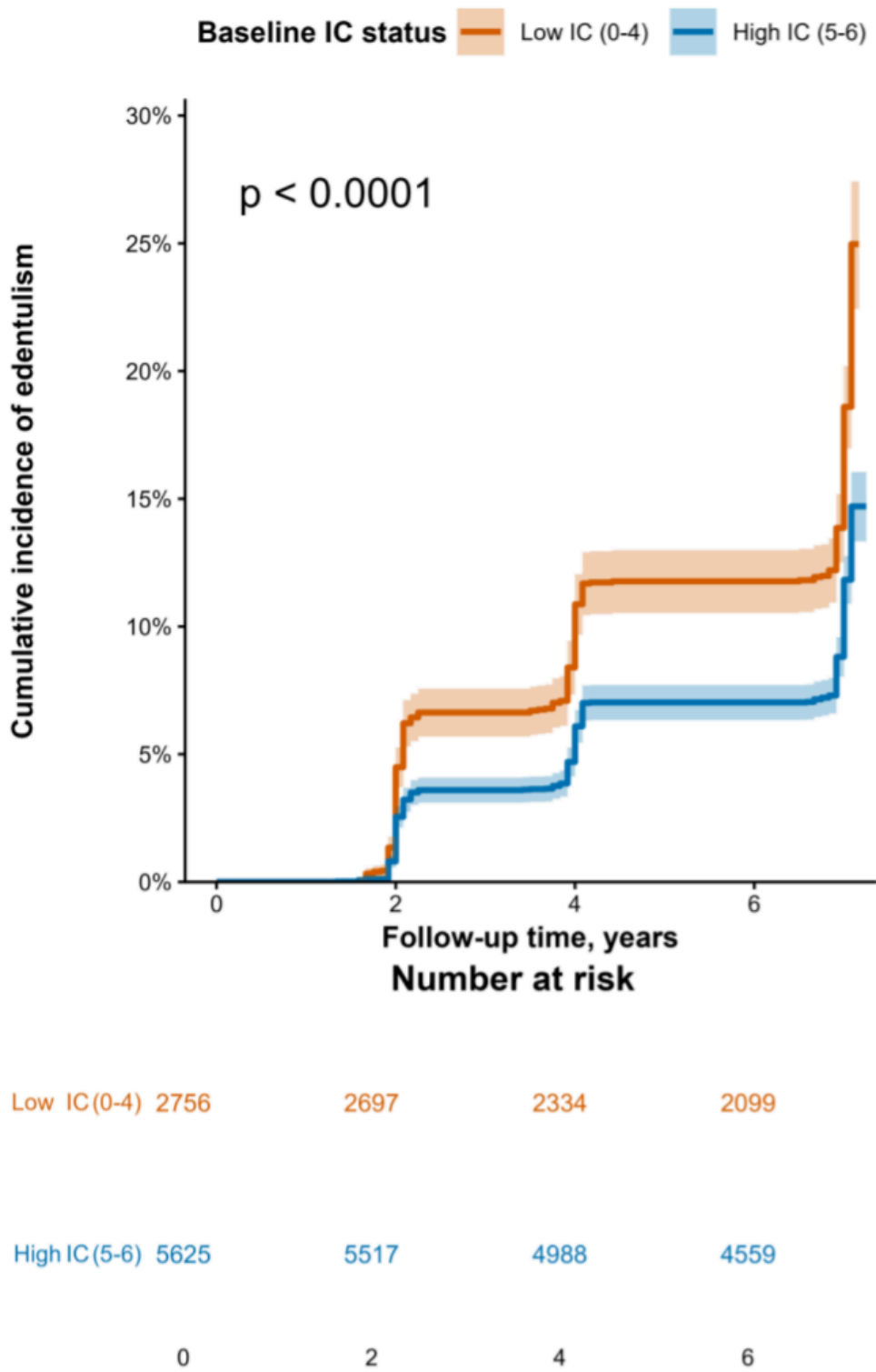


Figure 2

Cumulative incidence of edentulism by baseline IC status

Figure 3. Dose-response association between baseline IC and incident edentulism

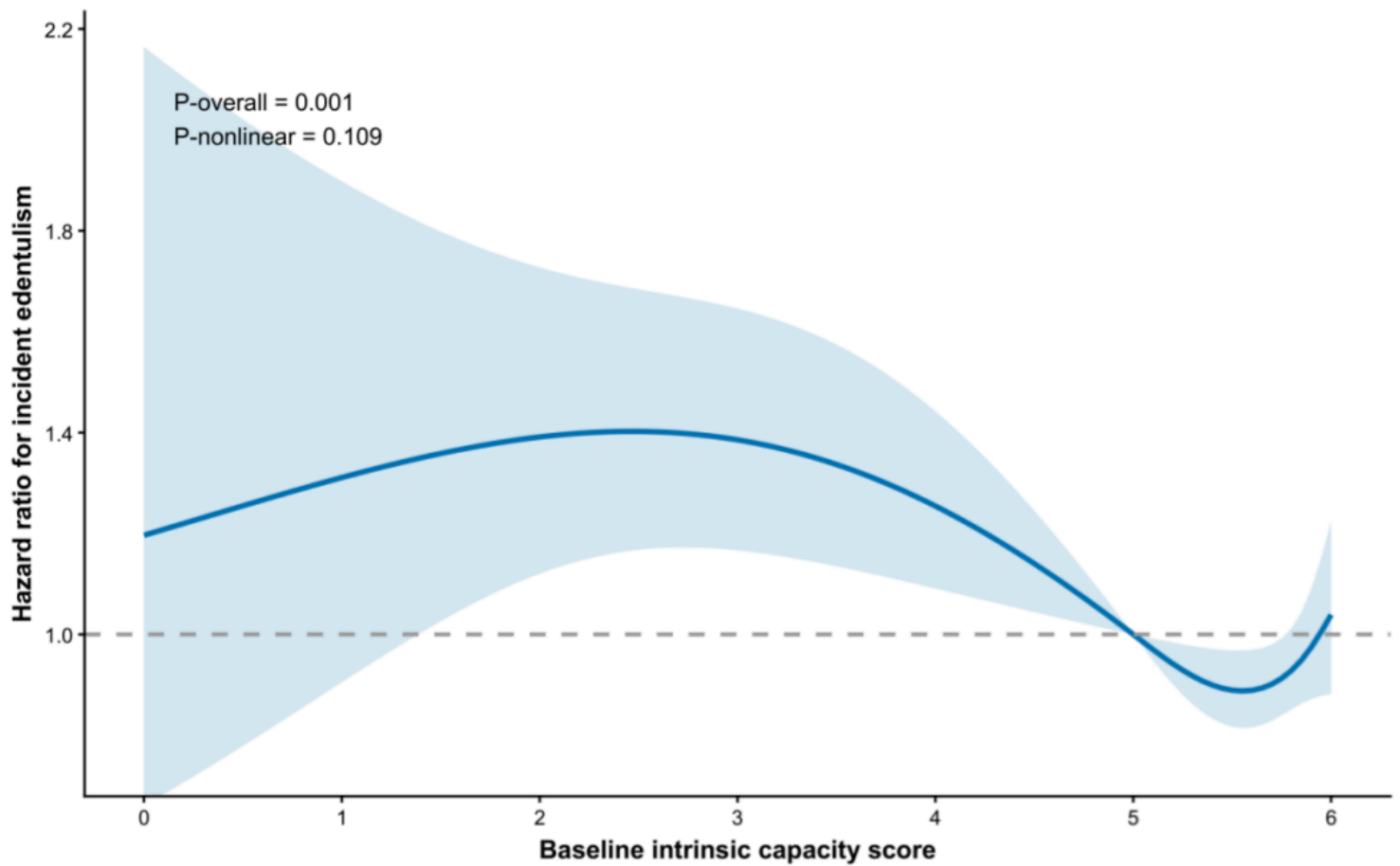


Figure 3

Dose-response association between baseline IC and incident edentulism

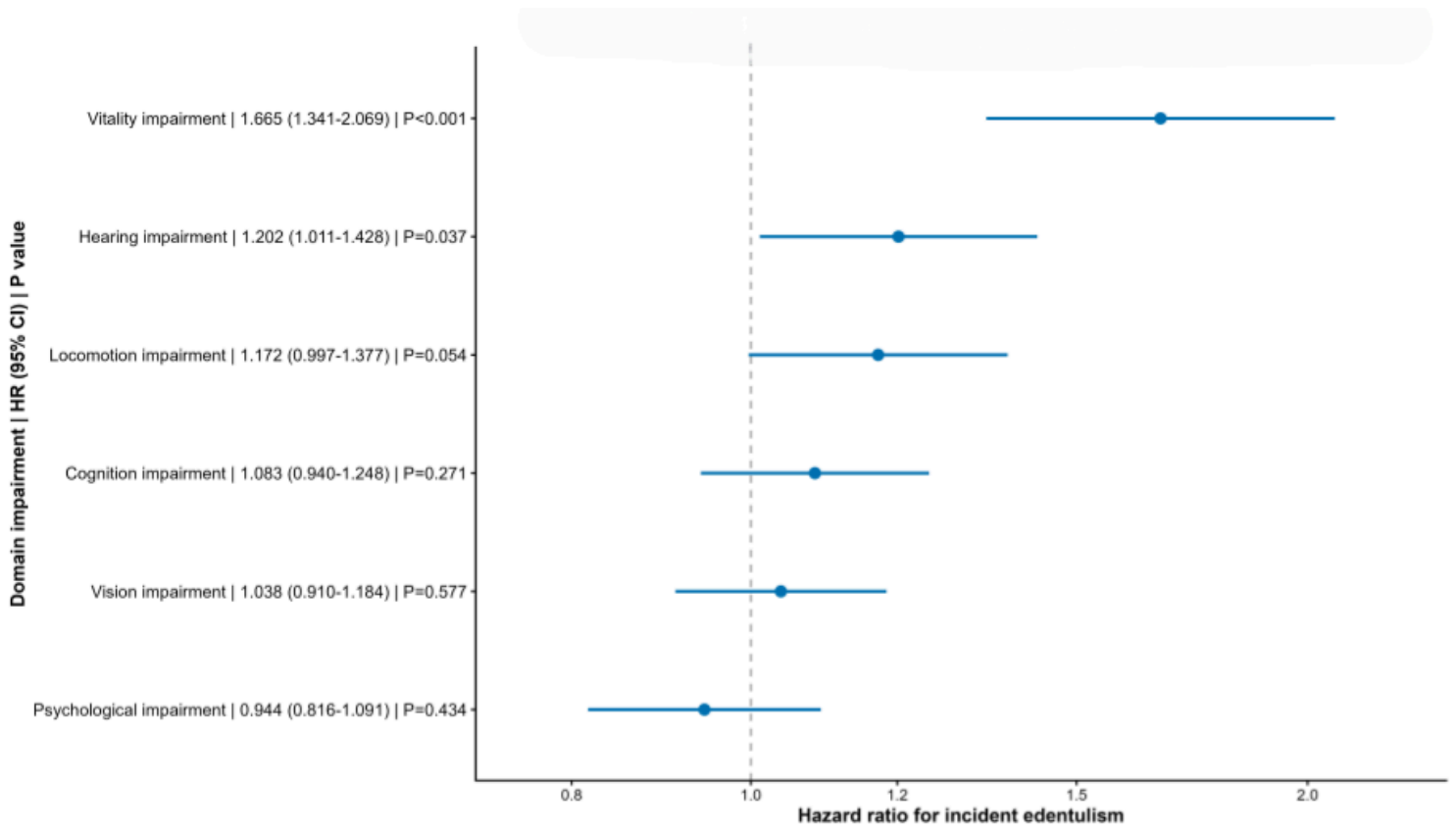


Figure 4

Mutually adjusted IC domain impairments and incident edentulism

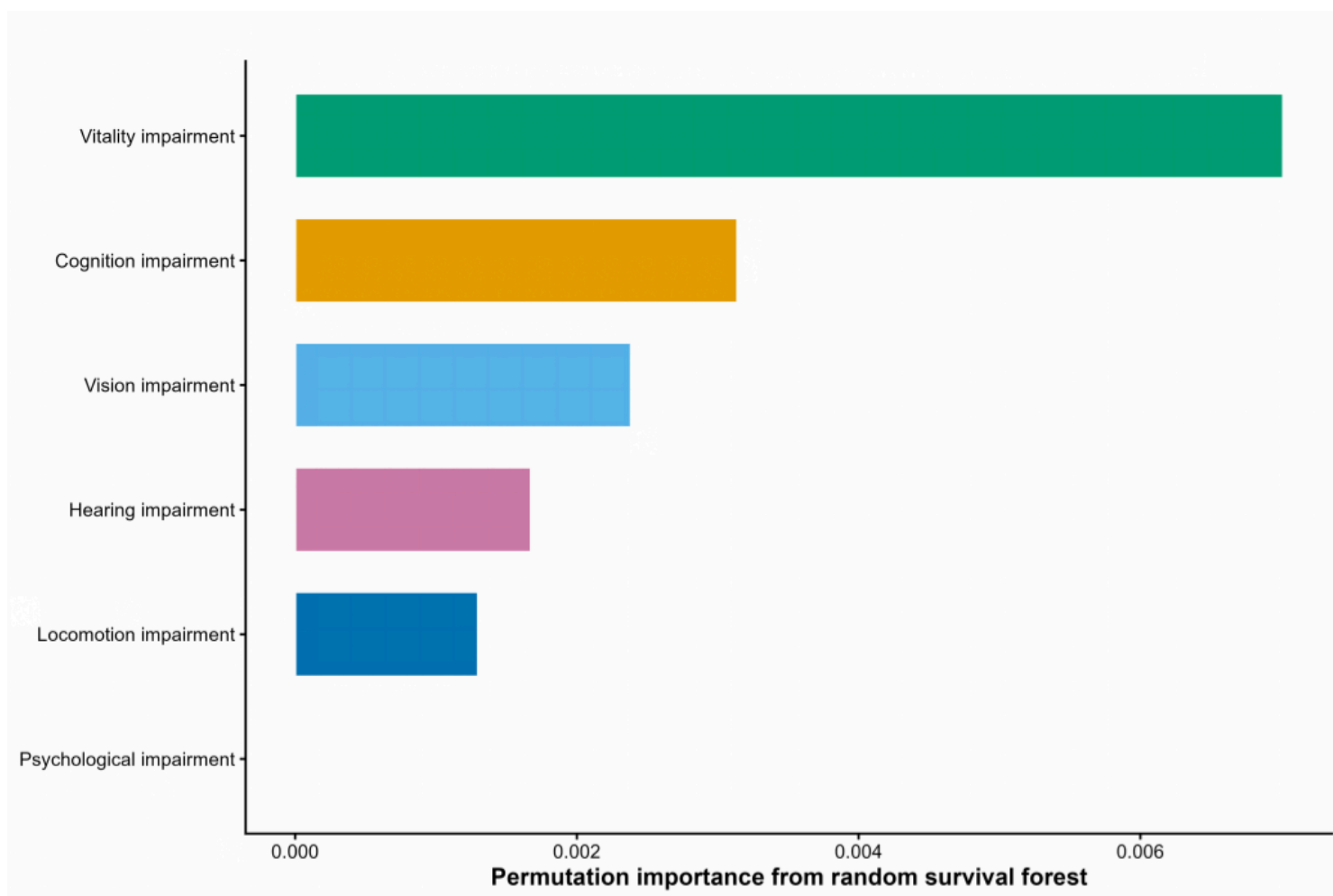


Figure 5

Relative predictive contribution of IC domains

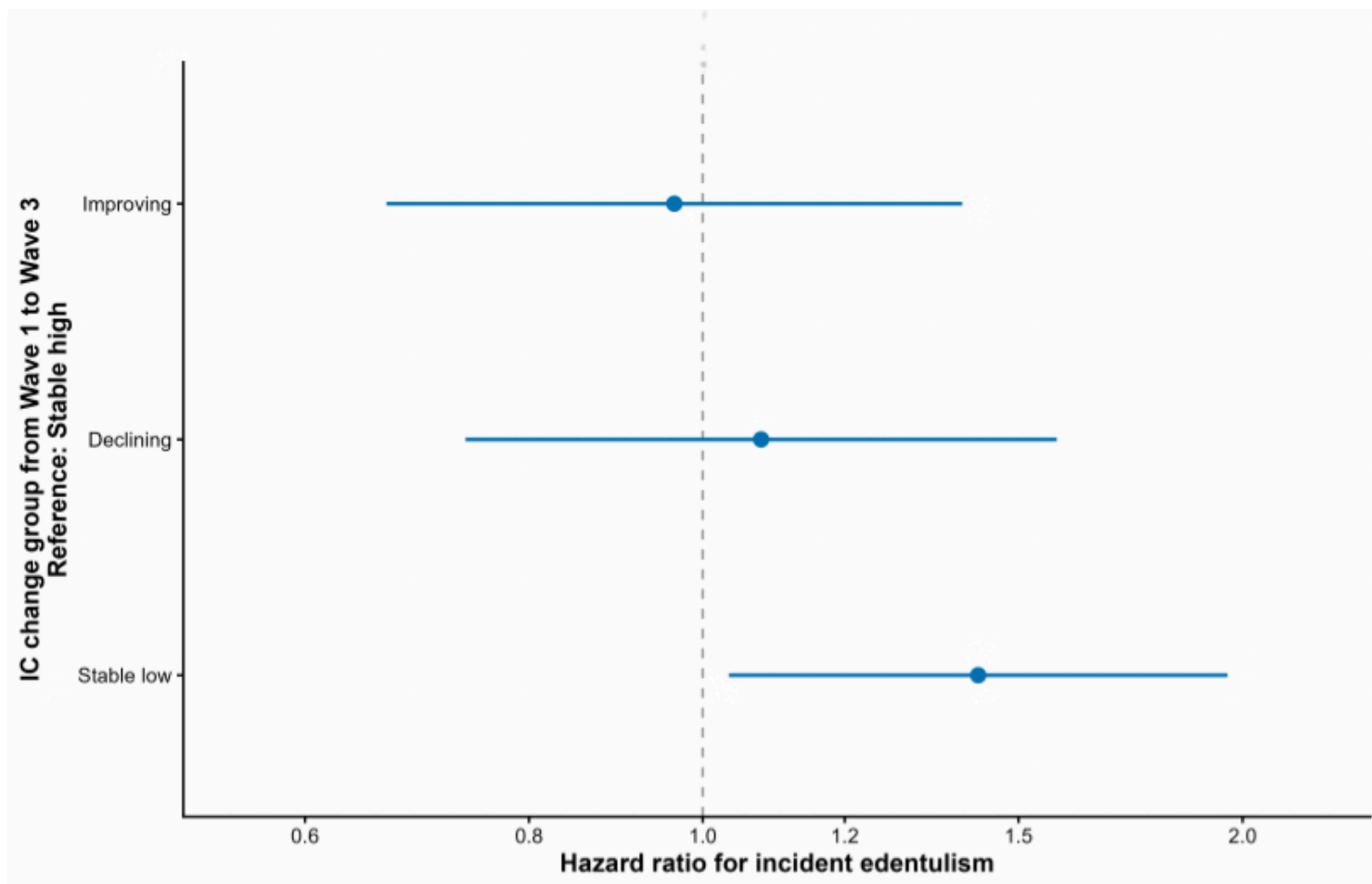


Figure 6

IC change groups and incident edentulism after Wave 3

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