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Original Article

Association of Life's Crucial 9 with All-Cause Mortality in U.S. Adults with Hypertension: A Nonlinear Dose-Response Analysis from NHANES 2005–2018

Yingjie Sheng[1,+], Ying Han[1,+], and Ye Xue[1,+*]

[1]Department of Cardiology, Jinqiu Hospital of Liaoning Province, Shenyang 110016, China

+These Authors Contributed Equally to this Work

[*]Corresponding Author: Ye Xue

Abstract:

Background: Life's Essential 8 (LE8) defines ideal cardiovascular health (CVH) by four behaviors and four factors; Life's Crucial 9 (LC9) expands LE8 by including psychological health, such as depression. Although higher CVH is linked to reduced mortality, this association may be nonlinear in hypertensive adults. We investigated the relationship between LC9 and all-cause mortality in U.S. adults with hypertension, hypothesizing an inverse, nonlinear association.

Methods: We analyzed 12,588 hypertensive adults (age ≥20) from NHANES 2005–2018. Cox proportional hazards models estimated hazard ratios (HRs) for all-cause mortality. Nonlinearity was evaluated by generalized additive models and two-piecewise Cox models.

Results: Participants' mean age was 59.8±14.8 years; 50.9% were female. Over a mean 7.1-year follow-up, 2,220 deaths (17.6%) occurred. Higher LC9 scores were significantly associated with lower all-cause mortality. In fully adjusted models, those in the highest LC9 tertile had a 31% lower mortality risk than the lowest (adjusted HR 0.69, 95% CI 0.59–0.81, P<0.001). A nonlinear dose-response association was observed. Two-piecewise Cox models identified an inflection at LC9 = 39.4. Below this, each 1-SD increase in LC9 was linked to a 34% lower hazard (HR 0.66, 95% CI 0.51–0.85). For LC9 ≥39.4, each 1-SD increase corresponded to a 12% risk reduction (HR 0.88, 95% CI 0.83–0.94).

Conclusions: Higher LC9 scores are associated with lower all-cause mortality in hypertensive U.S. adults, with a nonlinear relationship and diminishing returns at higher scores. Achieving a CVH threshold may benefit this population.

Keywords: Life's Essential 8; Life's Crucial 9; cardiovascular health; hypertension; mortality; nonlinearity; Cox model.

Introduction

Cardiovascular health (CVH) is a powerful determinant of longevity. The American Heart Association (AHA) introduced the concept of "ideal CVH" in 2010 as *Life's Simple 7* – a metric comprising four health behaviors (diet, physical activity, smoking status, body weight) and three health factors (blood pressure, cholesterol, blood glucose) [1] .Studies consistently showed that individuals meeting more ideal CVH metrics have substantially lower risk of cardiovascular disease and all-cause mortality [2.3] .In 2022, the AHA expanded this framework to *Life's Essential 8* by adding sleep health as an eighth metric and updating scoring methods [4]. Notably, psychological health was identified as a crucial omission from CVH indices. Emerging evidence links mental well-being (e.g., absence of depression or chronic stress) with cardiovascular outcomes [5.6]. To address this, experts have proposed *Life's Crucial 9 (LC9)* – integrating

mental health into CVH assessment [7]. The LC9 score incorporates the eight AHA metrics *plus* a mental health component (often quantified via depression symptom score), each scaled 0–100 and averaged, yielding an overall CVH score from 0 (worst) to 100 (best) [8]

Higher composite CVH scores (whether LS7, LE8 or LC9) generally predict lower mortality risk [1.4.8.9]. In a meta-analysis of 13 cohorts, each additional ideal LS7 metric was associated with an 11% reduction in all-cause mortality [10], supporting a *linear* inverse dose-response. Similarly, recent analyses using LE8/LC9 in US samples found that mortality risk decreases monotonically as CVH scores improve [8.11]. For instance, Ge *et al.* (2024) reported that each 10-point higher LC9 was associated with a 23% lower risk of all-cause mortality [8]. However, whether this relationship is strictly linear or exhibits thresholds is debated. Certain studies suggest diminishing returns at high CVH levels – i.e., going from poor to moderate CVH yields larger gains than going from moderate to ideal. In one study of older adults, the hazard reduction per additional CVH metric was greatest among those with the worst baseline profiles, hinting at nonlinearity [10]. On the other hand, many analyses have not detected significant nonlinear effects, treating CVH-mortality associations as linear across the spectrum [9.10].

Understanding potential threshold effects has practical implications. If a minimum CVH "threshold" exists beyond which extra improvement confers limited benefit, it would support prioritizing interventions to bring patients up to that threshold. Nonlinear associations have been observed in related contexts. Hu *et al.* (2020) found a U-shaped relationship between serum uric acid and mortality, with an inflection point separating harmful low vs. high levels [12]. For composite CVH scores, recent studies in specific populations indicated possible inflection points. For example, among individuals with metabolic syndrome, an inflection around LC9=70.56 was noted, with more pronounced risk reduction beyond that point [13]. In contrast, in a NAFLD (non-alcoholic fatty liver disease) cohort, LC9's association with mortality appeared linear, though a threshold (~60) was identified for NAFLD incidence risk [14]. These disparate findings underscore the need to evaluate nonlinearity in different groups.

Hypertensive adults are a high-risk population in whom CVH promotion is critical. Hypertension, by itself, confers elevated mortality risk, but this can be substantially modified by other CVH factors (weight, diet, etc.) [10.15]. However, hypertensive individuals may have unique profiles – e.g., many are older with entrenched risk factors – where the impact of achieving *some* improvement might be nonlinear. To the best of our knowledge, no prior study has specifically examined the LC9-mortality relationship in hypertensive adults, nor tested for threshold effects therein.

We aimed to analyzing the association between LC9 and all-cause mortality and evaluated whether the dose-response is linear or reaches a plateau. We hypothesized that higher LC9 would be inversely associated with mortality and that a point of diminishing returns might be observed.

Methods

Study Design and Population

We used data from NHANES 2005–2018, a series of nationally representative cross-sectional surveys of the U.S. population [16]. Baseline data were collected through standardized interviews, physical examinations, and laboratory testsfile. We included participants aged ≥20 years with hypertension. Hypertension was defined as having measured systolic blood pressure ≥140 mmHg or diastolic ≥90 mmHg, or self-reported use of antihypertensive medication. This definition aligns with the timeframe of our study (predating the 2017 ACC/AHA threshold change to 130/80). We excluded individuals with missing data on any of the LC9 components. The final analytic sample comprised **N=12,588** hypertensive adults. A flow diagram of participant selection is presented in **Figure 1** (see Supplementary Material). All participants provided written informed consent; NHANES protocols were approved by the NCHS Ethics Review Board. All data used in this study were de-identified and publicly available. The authors did not have access to information that could identify individual participants during or after data collection.

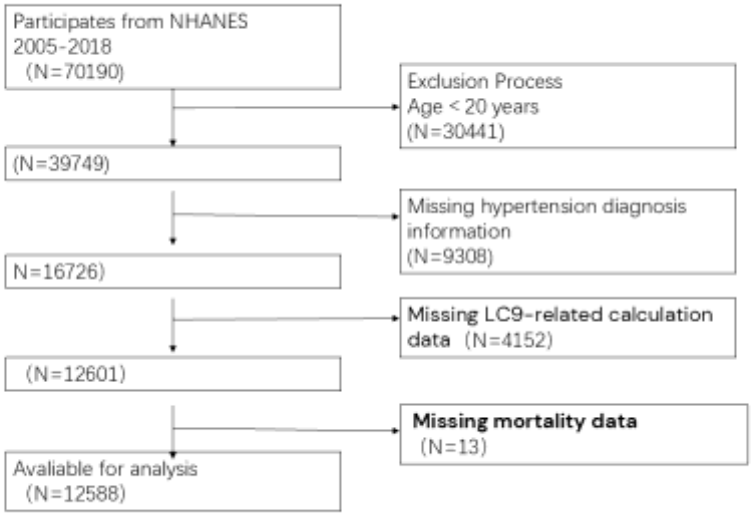

Figure1 . Flowchart of study population selection, NHANES 2005–2018

Measurement of Life's Crucial 9 (LC9) Score

The exposure of interest, LC9, is a composite CVH score integrating nine domains. We constructed the LC9 score according to published recommendations [13]. Briefly, we first calculated the LE8 score for each participant using AHA's algorithm [8]. The LE8 encompasses: (1) diet quality, (2) physical activity, (3) nicotine exposure, (4) sleep health, (5) body mass index, (6) blood pressure, (7) blood glucose, and (8) blood cholesterol. Each component was scored on a scale from 0 to 100 (poor to ideal) based on AHA criteria (e.g., meeting recommended levels yields a higher score) [13]. The overall LE8 score is the average of the eight component percentages (thus also ranging 0–100). We obtained necessary data from NHANES dietary recalls, accelerometry and questionnaire (for physical activity and sleep), clinical measurements, and blood tests to compute these scores, following the methods detailed by the AHA (2022) for LE8 scoring. Next, to incorporate mental health, we derived a psychological health score from the Patient Health Questionnaire-9 (PHQ-9), a validated depression symptom instrument administered in NHANES (available in 2005–2018 cycles). The PHQ-9 consists of 9 items scored 0–3; total scores range 0–27, with higher scores indicating worse depressive symptoms. We transformed the PHQ-9 into a mental health index from 0 to 100, with 100 representing optimal psychological well-being (PHQ-9 score of 0) and 0 representing severe depression (PHQ-9 score of 27). Specifically, we used the formula: Mental Health Score = $(27 - \text{PHQ-9 total}) / 27 \times 100$. Finally, the **LC9 score** was calculated as the mean of the LE8 score and the mental health score [8]. Thus, LC9 also ranges from 0 (worst CVH) to 100 (best CVH). For interpretability, in some analyses we categorized LC9 into tertiles (T1=lowest CVH to T3=highest CVH).

Outcome Ascertainment

The outcome was all-cause mortality. Mortality status and follow-up duration were ascertained by probabilistic record linkage with the National Death Index (NDI) [17]. Participants in NHANES 2005–2018 were followed for mortality through December 31, 2019. Person-months of follow-up were calculated from the NHANES exam date until date of death or censoring (December 31, 2019, or end of available follow-up). We calculated follow-up time in months and converted to years for reporting. Among the 12,588 hypertensive participants, there were **2,220 deaths** observed over a total of ~89,125 person-years of follow-up. The overall mortality rate was approximately 24.9 deaths per 1,000 person-years, consistent with the high-risk nature of a hypertensive cohort.

Covariates

Based on literature and directed acyclic graphs, we included several covariates to adjust for potential confounding. Demographic covariates

were: **age**, **sex**, **race/ethnicity**, **marital status**, **education level**, and **poverty-income ratio (PIR)**. Age was modeled as a continuous variable with a penalized spline term in Cox models (to flexibly adjust for its nonlinear association with mortality risk) [8]. Sex (male or female), race/ethnicity (categorized as Non-Hispanic White, Non-Hispanic Black, Mexican American , Other Hispanic, or Other Race), marital status (married/living with partner vs. not), and education (less than high school, high school graduate, more than high school) were included as categorical predictors. PIR (family income divided by poverty threshold) was treated as a continuous covariate (with spline adjustment in sensitivity analysis) and provides a measure of socioeconomic status. We also adjusted for **smoking status**, **alcohol use**, and **physical activity**, as these lifestyle factors could confound the relationship between LC9 (which includes some of these domains) and mortality. Smoking status was categorized as current, former, or never smoker. Alcohol use was categorized as heavy drinking vs. not, where heavy drinking was defined (for consistency with prior NHANES analyses [8]) as consuming ≥5 drinks per day on average (men) or ≥4 drinks/day (women) – roughly corresponding to ≥14 (men)/≥7 (women) drinks per week. Physical activity was quantified in MET-minutes per week from the Global Physical Activity Questionnaire data, then categorized for descriptive analyses as meeting recommended levels (≥150 min/week moderate-equivalent activity) or not. In fully adjusted models, we included physical activity as a continuous variable (log-transformed MET-min/week) to account for fine gradations.

Notably, LC9 itself incorporates several of these factors (smoking, activity, etc.). We elected to adjust for them to isolate the independent association of the composite score with mortality beyond the effects of any single component. This approach is conservative (potentially underestimating LC9's total effect) but helps identify whether LC9 predicts mortality through pathways *not entirely explained by* smoking, exercise, or other individual factors. We did not adjust for biomedical factors like blood pressure, blood glucose, or BMI separately, as these are integral to the LC9 score (adjusting for them would constitute over-adjustment). Likewise, we did not adjust for comorbid conditions (e.g., CVD, diabetes) that may lie on the causal pathway from LC9 to mortality. Our goal was to estimate the overall association of baseline CVH status (encompassing those factors and health status) with subsequent mortality.

Statistical Analysis

Baseline characteristics were summarized by tertiles of LC9. We tested differences across LC9 tertiles using Chi-square tests for categorical variables and One-Way ANOVA for continuous variables.

We used Cox proportional hazards regression to assess the association between LC9 and all-cause mortality. We verified that the proportional hazards assumption was satisfied for the LC9 variable and covariates via Schoenfeld residual tests. We constructed two primary models: Model 1, adjusting for age (smooth), sex, race/ethnicity, marital status, PIR, education only, and Model 2, adjusting for age (smooth), sex, race/ethnicity, marital status, PIR, education, smoking, alcohol use, and physical activity (i.e., all covariates). In exploratory analyses, we also ran an unadjusted model (univariate Cox with LC9 only) and observed similar patterns, albeit with slightly stronger effect sizes as expected. Results are reported from the fully adjusted Model 2 unless otherwise noted. We examined LC9 both as a continuous predictor (per 1-point increase and per 1–SD increase) and in categories (Tertiles).

To investigate potential nonlinear relationships, we employed two methods. First, we fitted a generalized additive model (GAM) with LC9 to visualize the dose-response curve. [12]. Second, we conducted a two-piecewise Cox regression approach. We used an iterative algorithm to identify the inflection point (threshold) in the LC9–mortality relationship. In brief, we tested potential inflection points by maximizing the model log-likelihood across the range of LC9, then confirmed the point where the model deviance was minimized and the two-piece model significantly improved fit over a single linear term (P<0.05 for likelihood ratio test). [8]

The two-sided alpha level was set at 0.05. All the statistical analyses were performed using the EmpowerStats (www.empowerstats.com, X&Y solutions, Inc. Boston MA) and R software version 3.6.1 (http://www.r-project.org).

Results

Baseline Characteristics

The study cohort included 12,588 hypertensive adults (mean age 59.8±14.8 years, 50.3% female). The racial/ethnic composition was 45.85% non-Hispanic White, 26.56% non-Hispanic Black, 11.77% Mexican American , 8.23% Hispanic, and 7.59% other. The mean LC9 score was 61.45 (SD ≈ 13.10, median 62.22). **Table 1** summarizes participant characteristics by tertiles of LC9. As expected, A greater proportion of females, non-Hispanic Black individuals, those with lower socioeconomic status, and unmarried participants were observed in the lowest LC9 tertile. This group also showed a substantially higher prevalence of current smoking (33.4% vs. 5.5%), heavy alcohol use (16.1% vs. 11.3%), physical inactivity (23.4% vs. 74.4% meeting guidelines), obesity (BMI 34.3 vs. 28.1 kg/m²), diabetes (49.1% vs. 15.7%), and hyperlipidemia (84.8% vs. 74.0%) compared to the highest tertile (all $P<0.001$). Educational attainment and income were also significantly lower. All-cause mortality was notably higher in the lowest LC9 group (22.8% vs. 13.4%, $P<0.001$). These results demonstrate a strong association between lower cardiovascular health and adverse sociodemographic, behavioral, and clinical factors.

Table 1. Baseline Characteristics of the Study Population by LC9 Tertiles.

LC9		Low T1	Middle T2	High T3	*P*-value
N	12588	4091	4234	4263	
Age (years)	59.78 ± 14.84	59.52 ± 14.00	60.07 ± 14.88	59.75 ± 15.56	0.244
LC9	61.45 ± 13.10	46.56 ± 7.50	61.81 ± 3.34	75.39 ± 5.86	<0.001
Body Mass Index(kg/m2)	31.08 ± 7.33	34.30 ± 8.14	31.12 ± 6.85	28.05 ± 5.46	<0.001
Person-Months of Follow-up from NHANES Interview date	85.60 ± 47.21	83.02 ± 47.65	85.97 ± 47.41	87.71 ± 46.47	<0.001
Sex					<0.001
Male	6187 (49.15%)	1839 (44.95%)	2136 (50.45%)	2212 (51.89%)	
Female	6401 (50.85%)	2252 (55.05%)	2098 (49.55%)	2051 (48.11%)	
Ethnicity					<0.001
Non-Hispanic White	5771 (45.85%)	1705 (41.68%)	1901 (44.90%)	2165 (50.79%)	
Non-Hispanic Black	3344 (26.56%)	1349 (32.97%)	1137 (26.85%)	858 (20.13%)	
Mexican American	1482 (11.77%)	487 (11.90%)	544 (12.85%)	451 (10.58%)	
Other Hispanic	1036 (8.23%)	331 (8.09%)	353 (8.34%)	352 (8.26%)	
Other Race	955 (7.59%)	219 (5.35%)	299 (7.06%)	437 (10.25%)	
MARITAL recoded					<0.001
Married/Living with Partner	7428 (59.01%)	2122 (51.87%)	2510 (59.28%)	2796 (65.59%)	
Widowed/Divorced/ Separated	3841 (30.51%)	1489 (36.40%)	1292 (30.51%)	1060 (24.87%)	
Never married	1313 (10.43%)	477 (11.66%)	431 (10.18%)	405 (9.50%)	
Missing	6 (0.05%)	3 (0.07%)	1 (0.02%)	2 (0.05%)	
Poverty income ratio					<0.001
Poor	2237 (17.77%)	1044 (25.52%)	704 (16.63%)	489 (11.47%)	
Nearly poor	3288 (26.12%)	1225 (29.94%)	1131 (26.71%)	932 (21.86%)	
Middle income	3193 (25.37%)	927 (22.66%)	1128 (26.64%)	1138 (26.69%)	
High income	2838 (22.55%)	546 (13.35%)	943 (22.27%)	1349 (31.64%)	
Missing	1032 (8.20%)	349 (8.53%)	328 (7.75%)	355 (8.33%)	
EDU recoded					<0.001
Below high school	1363 (10.83%)	567 (13.86%)	462 (10.91%)	334 (7.83%)	

High school	4992 (39.66%)	1924 (47.03%)	1737 (41.03%)	1331 (31.22%)	
Above high school	6224 (49.44%)	1599 (39.09%)	2030 (47.95%)	2595 (60.87%)	
Missing	9 (0.07%)	1 (0.02%)	5 (0.12%)	3 (0.07%)	
SMOKE recoded					<0.001
Never	6304 (50.08%)	1431 (34.98%)	2152 (50.83%)	2721 (63.83%)	
Former	3979 (31.61%)	1288 (31.48%)	1382 (32.64%)	1309 (30.71%)	
Now	2297 (18.25%)	1366 (33.39%)	698 (16.49%)	233 (5.47%)	
Missing	8 (0.06%)	6 (0.15%)	2 (0.05%)	0 (0.00%)	
Alcohol use recoded					<0.001
Never	1801 (14.31%)	550 (13.44%)	626 (14.79%)	625 (14.66%)	
Former	2643 (21.00%)	1086 (26.55%)	875 (20.67%)	682 (16.00%)	
Mild	4280 (34.00%)	1089 (26.62%)	1413 (33.37%)	1778 (41.71%)	
Moderate	1562 (12.41%)	493 (12.05%)	520 (12.28%)	549 (12.88%)	
Heavy	1769 (14.05%)	660 (16.13%)	626 (14.79%)	483 (11.33%)	
Missing	533 (4.23%)	213 (5.21%)	174 (4.11%)	146 (3.42%)	
Total physical activity (MET/week)					<0.001
<600	2304 (18.30%)	680 (16.62%)	884 (20.88%)	740 (17.36%)	
>=600	6167 (48.99%)	957 (23.39%)	2039 (48.16%)	3171 (74.38%)	
Missing	4117 (32.71%)	2454 (59.99%)	1311 (30.96%)	352 (8.26%)	
Diabetes Mellitus					<0.001
No	7301 (58.20%)	1757 (43.22%)	2438 (57.73%)	3106 (72.98%)	
Diabetes Mellitus	3972 (31.66%)	1994 (49.05%)	1312 (31.07%)	666 (15.65%)	
IFG(Impaired Fasting Glycaemia)	704 (5.61%)	197 (4.85%)	261 (6.18%)	246 (5.78%)	
IGT(Impaired Glucose Tolerance)	567 (4.52%)	117 (2.88%)	212 (5.02%)	238 (5.59%)	
Hyperlipidemia					<0.001
No	2467 (19.60%)	622 (15.21%)	738 (17.43%)	1107 (25.97%)	
Yes	10120(80.40%)	3468 (84.79%)	3496 (82.57%)	3156 (74.03%)	
Final Mortality Status					<0.001
Assumed alive	10368(82.36%)	3157 (77.17%)	3517 (83.07%)	3694 (86.65%)	
Assumed deceased	2220 (17.64%)	934 (22.83%)	717 (16.93%)	569 (13.35%)	

Data are mean ± SD or % (SE). Tertiles for LC9 mid（min-max）: T1 48.33 (11.67-55.56), T2 61.67 (56.11-67.22), T3 73.89 (67.78-100.00). *P*-values test differences across tertiles (weighted χ^2 for percentages, weighted linear regression for means).

Abbreviations: PIR, poverty-income ratio. Heavy alcohol use defined as ≥5 drinks/day (men) or ≥4 drinks/day (women). Physically active defined as ≥150 min/week moderate-equivalent activity.

These patterns suggest that long-standing social determinants and health behaviors contribute to overall CVH. We observed that even within a uniformly hypertensive sample, those with higher LC9 tended to have their hypertension in the context of otherwise optimal factors (e.g., normal weight, no smoking, etc.), whereas those with low LC9 often had multiple co-occurring risk factors.

During a mean follow-up of 7.13 years (median 7.08, interquartile range 4.3–9.7 years), a total of 2,220 participants died (unweighted percentage 17.64%). The crude all-cause mortality rate was 24.9 per 1,000 person-years. Mortality incidence differed strikingly by baseline LC9 tertile: The mortality rates per 1,000 person-years were 33.0 in the lowest LC9 tertile, 23.6 in the middle tertile, and 18.3 in the highest tertile. These findings indicate a clear inverse association between LC9 score and all-cause mortality, with participants in the lowest tertile experiencing almost twice the mortality rate compared to those in the highest tertile. These descriptive results already indicate an inverse association between

LC9 and mortality risk. Below, we present multivariable analyses quantifying this association and examine its shape.

Association of LC9 with All-Cause Mortality

In Cox regression models adjusted for demographic factors only (Model 1: age (smooth), sex, race/ethnicity, marital status, PIR, education), LC9 was significantly inversely associated with mortality risk. When modeled as a continuous variable, each 1-point increase in LC9 corresponded to a 3% reduction in mortality risk (Model 1 HR=0.97, 95% CI: 0.97–0.98, *P*<0.0001) (see **Table 2**). This association remained robust after full adjustment for all covariates. In the fully adjusted model (Model 2), each 1-point increase in LC9 was associated with a 1% reduction in mortality risk (HR=0.99, 95% CI: 0.98–0.99, *P*<0.0001). For reference, a 10-point difference in LC9 is roughly equivalent to gaining or losing approximately 1–2 ideal health metrics (i.e., about 3–4 ideal metrics vs. about 1–2 ideal metrics) on a 0–100 scale. An increase of 1 standard deviation in LC9 was associated with a 24% lower risk of all-cause mortality in Model 1 (HR=0.76, *P*<0.0001) and a 10% lower risk in Model 2 (HR=0.90, *P*<0.0001). Thus, even after comprehensive adjustment for potential confounders, overall cardiovascular health as measured by LC9 remains an independent predictor of survival among adults with hypertension.

Table 2. Hazard ratios for all-cause mortality by LC9 (continuous and Tertiles).

Exposure	Adjust I	Adjust II
LC9	0.97 (0.97, 0.98) <0.0001	0.99 (0.98, 0.99) <0.0001
LC9 tertile		
Low (T1)	1.0	1.0
Middle (T2)	0.66 (0.59, 0.72) <0.0001	0.81 (0.73, 0.90) 0.0001
High (T3)	0.48 (0.43, 0.54) <0.0001	0.76 (0.67, 0.87) <0.0001
LC9 tertile continuous	0.69 (0.66, 0.73) <0.0001	0.87 (0.81, 0.93) <0.0001

Adjust I model adjust for: Age (years); Sex; Ethnicity; MARITAL recoded; Poverty income ratio; EDU recoded
Adjust II model adjust for: Age (years); Sex; Ethnicity; MARITAL recoded; Poverty income ratio; EDU recoded; SMOKE recoded; Alcohol use recoded; Total physical activity(MET/week)

When LC9 was categorized into tertiles, a pronounced inverse gradient in mortality risk was observed across increasing LC9 groups. In the fully adjusted analyses, participants in the lowest LC9 tertile (T1) had the highest risk of all-cause mortality and served as the reference group (HR=1.00). Relative to T1, those in the middle tertile (T2) exhibited a 19% lower risk of death (HR=0.81, 95% CI: 0.73–0.90, *P*=0.0001), while participants in the highest tertile (T3) had a 24% lower risk (HR=0.76, 95% CI: 0.67–0.87, *P*<0.0001). The trend across tertiles was highly significant (*P* for trend <0.001).

In the minimally adjusted model (adjusted for age (smooth), sex, race/ethnicity, marital status, PIR, education), the associations were even more pronounced: T2 and T3 had hazard ratios of 0.66 (0.59–0.72, *P*<0.0001) and 0.48 (0.43–0.54, *P*<0.0001).

Nonlinear Dose-Response and Threshold Effect

Visual examination of the GAM spline plot suggested a curvilinear association between LC9 and mortality (**Figure 2**). The log-relative hazard declined steeply as LC9 increased from low values and began to level off around the higher end of the LC9 range. Statistically, the test for nonlinearity was significant (*P*=0.01 for the spline vs. linear model comparison), indicating that a nonlinear model fit the data better than a simple linear term. We therefore proceeded to characterize the relationship with a two-piecewise model.

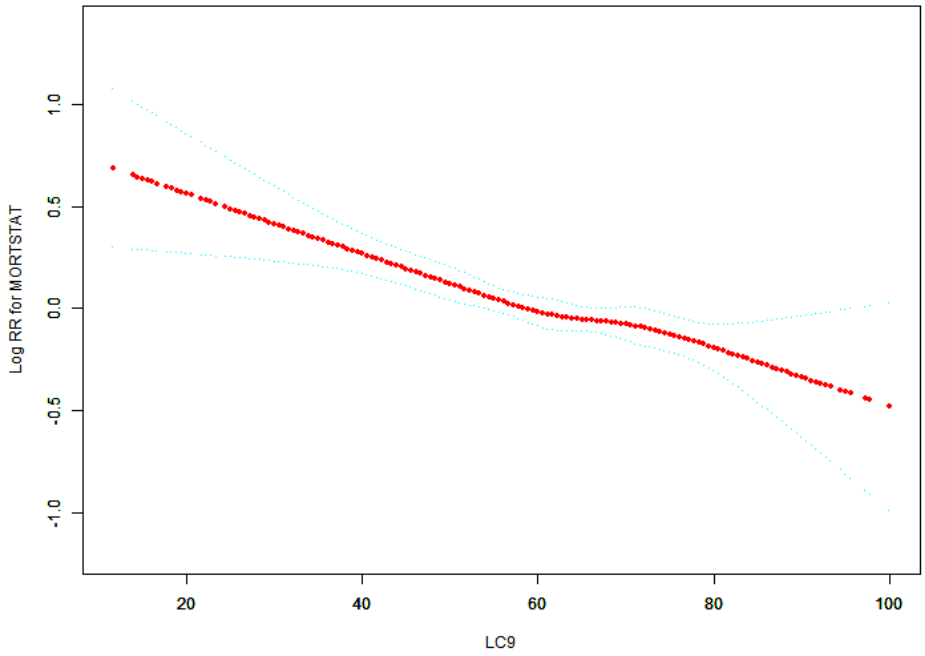

Figure 2：Association between LC9 score and log relative risk of mortality

The two-piece Cox regression identified an **inflection point at LC9 = 39.44**. LC9≈39.44 is within the range that AHA might classify as "poor CVH" (<50). Below this threshold, the mortality risk dropped rapidly with increasing LC9. In this segment (LC9 <39.4), the **hazard ratio per 1-point increase in LC9 was 0.97 (95% CI 0.95–0.99)** – a substantial risk reduction of 3% for each 1-point improvement (P=0.0011). By contrast, **above the threshold (LC9 ≥39.44)**, the slope was much gentler: the **HR per 1-point increase was 0.99 (0.99–1.00)**, corresponding to a 1% risk reduction per 1-point (P<0.0001). The difference in slopes was statistically significant (P<0.05 for interaction).

Discussion

In this large nationally representative cohort of hypertensive U.S. adults, we found that a higher Life's Crucial 9 score – indicating better overall cardiovascular health, including mental well-being – was associated with significantly lower all-cause mortality. To our knowledge, this is the first study focusing on LC9 and mortality specifically in individuals with hypertension. Our findings extend and enrich the evidence base in several ways. We demonstrated that the LC9–mortality relationship is **nonlinear**, with a clear threshold effect around an LC9 score of ~39. There appears to be a point (approximately the boundary between poor and intermediate CVH) beyond which the mortality returns on further improvement begin to plateau. In practical terms, going from a very low LC9 (extremely unhealthy lifestyle and uncontrolled risk factors) to a moderate LC9 (addressing the most critical risk factors) yields a larger mortality risk reduction than going from moderate to near-perfect CVH.

Our results resonate with prior literature on CVH metrics and outcomes, while also adding new context. Previous studies on AHA's Life's Simple 7 reported a graded inverse association with mortality, often assuming linearity [10]. For example, in an analysis of NHANES 1999–2004, Ford *et al.* found that individuals with 6–7 ideal metrics had an ~79% lower mortality risk than those with 0 metrics [2] – implying a strong gradient but not directly testing nonlinearity. A meta-analysis by Guo L *et al.* (2017 similarly found a linear dose-response between number of ideal metrics and mortality risk [10]. Our finding of diminishing returns at higher LC9 might seem at odds with those linear models. However, it is important to note differences in exposure distribution and population. Hypertensive adults generally have lower CVH scores than the general population; very few in our sample had truly ideal CVH (LC9 in the 90s). Thus, the plateau we

observe at high LC9 might reflect a range where data are sparse or participants are a select (healthier) subset. Still, the inflection ~39 is well within the data-rich range and appears robust. Interestingly, a recent study of stroke survivors reported a combination of linear and nonlinear associations for LC9 with outcomes [18]. In that study, the authors noted an inverse association between LC9 and mortality, but hinted that after a certain point the benefits tapered (though formal threshold analysis was not done). Likewise, Wang *et al.* (2025) observed a curvilinear relationship between LC9 and metabolic syndrome prevalence, with an inflection around LC9≈70 [13]. In their case, effects were *more pronounced after the inflection*, meaning improvements beyond 70 gave even larger benefits for metabolic syndrome – a pattern opposite to our mortality findings. This discrepancy highlights that the shape of the relationship may differ by outcome. Metabolic syndrome is a mid-term health status outcome, whereas mortality is the ultimate outcome influenced by many accumulating factors. It is plausible that once someone achieves moderately good CVH, the additive benefit on mortality of becoming truly optimal is smaller due to ceiling effects (e.g., once major risk factors are controlled, residual risk might be governed by genetics or age). In contrast, for metabolic syndrome (a reversible condition), pushing CVH into the excellent range might dramatically resolve metabolic abnormalities, hence a steeper effect post-threshold. Our findings specifically indicate that for preventing death in hypertensive individuals, "good enough" CVH may suffice – i.e., getting out of the danger zone of very poor CVH is the critical step.

An intriguing aspect of our study is the threshold LC9 ~39. This value is notably lower than what one might expect; it is well below the midpoint of the LC9 scale. In fact, 39 corresponds to having a majority of CVH metrics in poor ranges. Why would the curve flatten after ~40, rather than later? One hypothesis is **survivor bias**: hypertensive individuals who score very high on LC9 are relatively rare and might be inherently robust (possibly a "healthy survivor" effect). Thus, differences among them are harder to detect – they all have good prognosis, and competing risks might dominate. Meanwhile, moving from extremely poor to moderately poor CVH among hypertensives could involve addressing something as critical as smoking cessation or starting blood pressure medications, which yields a big mortality payoff. Another contributing factor might be measurement limitations: LC9 compresses a lot of information, and beyond a certain score, it may not discriminate risk well in this population. For instance, whether someone's score is 70 or 90, they likely have all major risk factors controlled (the latter might just be a bit better in one area), and their mortality risk could be similarly low over the follow-up horizon. In contrast, someone with LC9 of 30 likely has multiple uncontrolled risks (e.g., still smoking *and* poorly controlled hypertension *and* obesity), dramatically raising short-term mortality risk (due to stroke, myocardial infarction, etc.). This would create a nonlinear shape as observed.

Our findings have practical implications. For clinicians managing hypertensive patients, the data underscore the importance of comprehensive risk factor management. While controlling blood pressure is paramount, patients with hypertension often have other suboptimal health metrics (as seen in our T1 group). Our results suggest that helping these patients improve from "terrible" to "just okay" CVH could significantly extend their lives. In concrete terms, assisting a hypertensive smoker with obesity and uncontrolled diabetes (LC9 ~20–30) to quit smoking, lose some weight, and control glucose (maybe raising LC9 to ~50) might cut their mortality risk by nearly half. On the other hand, pushing a patient who already doesn't smoke, eats fairly well, exercises, and has controlled risk factors (LC9 ~70) to make further minor improvements (to LC9 ~85) might yield only marginal mortality benefit – though it could have other benefits like better quality of life. Therefore, a triage approach could be considered: identify hypertensive individuals with very low CVH scores and prioritize them for intensive multifactorial intervention (smoking cessation programs, dietary coaching, physical activity support, medication optimization, and mental health services). This is aligned with precision medicine and public health resource allocation – focusing on those at highest risk. Of course, this doesn't mean those with intermediate CVH should be neglected, but it suggests diminishing returns as one approaches ideal metrics. From a public health perspective, community interventions that shift the distribution of CVH rightward, especially pulling the left tail (worst CVH) up, could

substantially reduce mortality in the hypertensive population.

It is also worthwhile to compare our threshold effect with thresholds reported in other studies. Hu *et al.* (2020) found an optimal range of serum uric acid (inflection ~5.7 mg/dL) beyond which risk increased again [12], indicating a U-shaped relation. In our case, we did not observe an uptick at high LC9 – no evidence of harm from extremely good CVH (which makes sense, as one cannot "overdose" on healthy behavior in the way one can have too low uric acid or too low BMI, for example). The plateau we saw is more akin to a *floor effect* on risk (once risk is low, it can't go much lower given background hazards). Interestingly, another recent NHANES analysis on LC9 in NAFLD patients noted a breakpoint at LC9 ~60 for NAFLD risk, with more pronounced benefits beyond that for NAFLD reduction [14], but they found the LC9-mortality link in NAFLD to be linear. Our hypertensive cohort shows the opposite – a breakpoint for mortality but likely a linear relation for say stroke incidence (not measured here). This suggests the possibility that threshold phenomena might differ by disease process. For mortality, once one achieves moderate health, other factors (age, genetics, medical therapy) might dominate risk, leading to plateau. For incidence of a specific condition (like NAFLD or metabolic syndrome), thresholds might occur at different points if pathophysiology has nonlinear triggers. Further research is needed to confirm these nuances.

Strengths and Limitations: Key strengths of our study include the large sample size drawn from a nationally representative survey, allowing generalizability to U.S. hypertensive adults. We had detailed measurements enabling construction of the LC9 score and adjustment for multiple confounders. The prospective design with ~7 years median follow-up captured a substantial number of events (2,220 deaths), providing adequate power to detect even moderate associations and nonlinearity. We employed advanced modeling (splines, segmented Cox) to rigorously assess the dose-response shape, adding to the methodological literature on CVH metrics. Moreover, use of LC9 – a comprehensive health index including mental health – is novel in this context and addresses a more holistic view of health than earlier metrics.

However, several limitations merit discussion. First, the observational design precludes causal inference. While we adjusted for many factors, residual confounding is possible. Unmeasured factors (e.g., quality of hypertension treatment, psychosocial stress, or inflammation) might influence both CVH score and mortality. Second, LC9 and covariates were measured at baseline only; we could not account for changes in CVH over time. Some participants may have improved or worsened their lifestyle after baseline (especially if diagnosed with conditions during follow-up), which could attenuate observed associations. Our analysis assumes baseline LC9 reasonably represents longer-term patterns. Relatedly, our follow-up of 7 years, while considerable, might not capture very long-term benefits of excellent CVH (perhaps why differences above LC9 80 were small in this timeframe). Third, the LC9 scoring algorithm we used mirrors the AHA's method for LE8 and a straightforward PHQ-9 conversion. It's possible that different weighting of components could yield a different threshold. For instance, if mental health were given less weight, the threshold might shift a bit. Fourth, our threshold determination, while statistically supported, has some uncertainty (confidence interval spanned mid-30s to low-40s). We caution against over-fixating on 39.44 as a precise number; conceptually, it indicates that the lowest quartile (roughly LC9 <40–45) is where risk escalates markedly. This overlaps with what AHA would classify as "poor CVH" (≤50). Indeed, using the AHA cut-off of 50, we found those <50 had significantly higher mortality than those ≥50, though our data suggest the critical cut-point might be even lower for mortality outcomes in this group.

Another limitation is our reliance on self-reported data for some lifestyle factors (diet, physical activity, smoking, alcohol). Measurement error in these could attenuate component–outcome relationships, although by combining them into LC9, we get a more robust aggregate measure. We also did not delve into cause-specific mortality due to limited numbers for specific causes; it would be interesting in future research to see if CVH nonlinearity varies by cause of death (e.g., perhaps strongly nonlinear for CVD death but not for cancer death). Prior research indicates ideal CVH has more impact on cardiovascular than cancer mortality[10].

Lastly, while we focused on hypertension, our findings might not apply to those without hypertension. For normotensive individuals, the threshold for mortality benefit of CVH might be at a different point or the relationship could even be linear throughout, as some prior works on general populations suggest [10]. Hypertension could amplify the harms of poor CVH in a nonlinear fashion (e.g., acting synergistically with smoking or obesity to sharply increase risk when both are present). Indeed, our lowest LC9 group likely had multiple co-risk factors *in addition to* hypertension, putting them at extremely high absolute risk – which then drops quickly if any of those factors are mitigated. In a person without hypertension, the baseline risk is lower, and the CVH–mortality curve might look different. Therefore, caution is needed in extrapolating our threshold to other groups.

In conclusion, we demonstrated that Life's Crucial 9 is a valuable summary index of cardiovascular health in hypertensive adults. Our findings reinforce that "what's good for the heart is good for longevity" – even for those already at elevated risk. Moreover, we uncovered a noteworthy nonlinear pattern: the inverse association between LC9 and mortality is steep initially and then plateaus, indicating diminishing marginal returns at higher CVH levels. This nuance does not diminish the importance of striving for ideal CVH, but it does inform strategy: prioritize improving the worst CVH profiles to save lives.

Author contributions

Y. S. and Y. X. designed the study. Y. S. wrote the manuscript. Y. S. and Y. H. collected, analyzed, and interpreted the data. Y. X. critically reviewed, edited, and approved the manuscript. All authors read and approved the final manuscript.

Conflict of Interest Statement:

The authors declare no conflict of interest.

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Data availability

The datasets generated and analyzed in the current study are available at NHANES website: https://www.cdc.gov/nchs/nhanes/index.htm.

What is Already Known on this Topic: Previous studies show that better cardiovascular health (CVH), often measured by composite scores, is linked to lower mortality. Life's Crucial 9 (LC9) provides a more comprehensive CVH metric by including both behavioral, biological, and psychological components. However, limited evidence exists on the nonlinear association between LC9 and mortality in hypertensive adults.

What this Study Adds: This study finds a strong, nonlinear association between higher LC9 scores and lower all-cause mortality in U.S. adults with hypertension. The greatest risk reduction occurs as LC9 scores improve from low to moderate, with benefits plateauing beyond a certain threshold.

How this Study Might affect Research, Practice or Policy: Targeted health interventions for hypertensive adults with the lowest LC9 scores could maximize survival benefits. This threshold insight offers clinical and public health guidance to prioritize improving CVH among those at greatest risk

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