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Original Research

Associations Between Accelerometer-Measured 24-Hour Movement Behaviors and Cardiac Conduction Disease in the UK Biobank Cohort

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AUTHOR'S SUMMARY

This is the first study to comprehensively investigate the impact of a 24-hour movement behavior hierarchy on the risk of cardiac conduction disease (CCD) using wrist-worn accelerometer-measured data, enabling more precise exposure assessment and compositional analysis. We found that higher moderate-to-vigorous intensity physical activity was associated with a lower risk of CCD, whereas sedentary behavior was associated with an increased risk, with these associations partly supported by changes in electrocardiographic parameters. Substituting sedentary time with physical activity may effectively prevent cardiac conduction abnormalities. Clinicians should emphasize the importance of regular physical activity and reducing sedentary time to maintain cardiac conduction health.

ABSTRACT

Background and Objectives: Daily activity has a distinct hierarchy of movement behaviors. The association between 24-hour movement behaviors and cardiac conduction disease (CCD) remains unclear. We aimed to investigate the association between accelerometer-measured 24-hour movement behaviors and CCD risk.
Methods: A total of 92,436 UK Biobank participants who wore wrist accelerometers for 7 consecutive days were included, with a median follow-up of 6.1 years. Multivariable Cox proportional hazards models were used to investigate the associations between 24-hour movement behaviors (sleep, sedentary behavior, light-intensity physical activity [LIPA], and moderate-to-vigorous intensity physical activity [MVPA]) and the risk of CCD. Compositional data analysis was performed to estimate the effects of reallocating time among 24-hour movement behaviors.
Results: Among the 92,436 participants (median age 58 years; interquartile range, 50–63; 54% female), 1,442 developed incident CCD (2.58 per 1,000 person-years) during the follow-

up. Greater sedentary behavior was associated with an increased risk of CCD (hazard ration [HR], 1.05; 95% confidence interval [CI], 1.02–1.08), whereas higher MVPA was associated with a lower risk (HR, 0.83; 95% CI, 0.75–0.92). Sleep duration and LIPA were not significantly associated with CCD risk. Reallocating 30 min/day to MVPA from other movement behaviors was associated with a 4% lower risk of CCD (HR, 0.96; 95% CI, 0.93–0.98). Conversely, reallocating 30 minutes/day to sedentary behavior was associated with a 3% increased risk (HR, 1.03; 95% CI, 1.01–1.05). Similar patterns were observed for specific CCD outcomes, including second- or third-degree atrioventricular block and pacemaker implantation.

Conclusions: Higher volumes of MVPA were associated with a lower risk of CCD, whereas increased sedentary behavior was associated with higher risk, highlighting the importance of preventive activity patterns.

Keywords: Cardiac conduction system disease; Physical activity; Sedentary behavior; UK Biobank

INTRODUCTION

Cardiac conduction disease (CCD), most attributed to fibrosis in conduction tissues, contributes significantly to morbidity and mortality and is increasingly recognized as a critical concern in the context of global population aging.1)2) Previous studies have identified risk factors for CCD, including age, poorly controlled blood pressure or glucose, and obesity, revealing that these conditions contribute to an elevated risk of disease in the cardiac conduction system.3-5)

Regular physical activity (PA) is a well-established, modifiable cornerstone of cardiovascular disease (CVD) prevention. Numerous studies have demonstrated its beneficial effects in reducing mortality and morbidity across different populations, including older adults and those with specific cardiovascular conditions.6-12) Recent studies suggest that PA may help prevent cardiac bradyarrhythmias, including CCD.5)13) Although the findings of these studies are not entirely consistent, evidence indicates that greater PA intensity and duration may offer protective effects against CCD. However, a major limitation of these studies is their reliance on self-reported PA data, which are susceptible to recall bias.

Most current global guidelines14)15) have recently focused on a hierarchy of 24-hour movement behaviors that aim to account for interconnections across multiple behaviors. This perspective highlights the need for more accurate assessment of 24-hour movement behaviors. To investigate these aspects, we used accelerometer-measured PA data, providing objective and precise quantification of daily movement behaviors, and examined the associations between the four components of 24-hour movement behaviors (sleep, sedentary behavior, light-intensity physical activity [LIPA], moderate-to-vigorous intensity physical activity [MVPA]) and CCD. This study comprehensively explored the impact of 24-hour movement behavior hierarchy on the risk of CCD.

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Conflict of Interest

Boyoung Joung has served as a speaker for Bayer, BMS/Pfizer, Medtronic, and Daiichi-Sankyo and has received research funds from Medtronic and Abbott. No fees were received, either directly or personally. The authors declare no conflicts of interest.

Data Sharing Statement

The data that support the findings of this study are available from the UK Biobank project site, subject to the registration and application processes. Further details are available at https://www.ukbiobank.ac.uk.

Author Contributions

Conceptualization: Kim M, Joung B; Data curation: Jang E, Yang PS, Joung B; Formal analysis: Kim M, Kim J, Joung B; Funding acquisition: Joung B; Investigation: Kim M, Kim J, Kim D, Yang PS, Joung B; Methodology: Kim M, Kim J, Kim D, Yang PS, Joung B; Project administration: Kim M, Kim J, Yang PS, Joung B; Resources: Jang E, Kim D, Joung B; Software: Kim M, Kim J, Jang E, Yang PS; Supervision: Kim J, Kim D, Yang PS, Joung B; Validation: Kim M, Kim J, Joung B; Visualization: Kim M, Kim J; Writing - original draft: Kim M, Kim J, Joung B; Writing - review & editing: Kim M, Kim J, Yang PS, Joung B.

METHODS

Ethical statement

This study was conducted in accordance with the Declaration of Helsinki (2013) and approved by the Institutional Review Board of the Yonsei University Health System (4-2024-0999). The current study has been conducted using the UK Biobank resources under application No. 77793, and written informed consent was obtained from all participants.

Study population

From 2006 to 2010, 502,421 participants, aged 40 to 69, were recruited for the UK Biobank cohort from 22 different assessment centers across England, Scotland, and Wales. The specifics of the study's methodology and data gathering have been previously documented.16) All participants underwent an initial assessment that included a touchscreen questionnaire, an oral interview, and physical measurements. They also provided data reflecting socioeconomic and ethnic diversity, an urban-rural mix, and baseline blood, urine, and saliva samples. After this initial baseline assessment, participants were monitored through their medical records, including hospital records and death registries. Accelerometer data were collected from a randomly selected subset of participants who had valid email addresses, with data collection taking place between February 2013 and December 2015, median 5.6 years (interquartile range [IQR]: 4.8–6.4) after their initial enrollment in the main study. The following exclusion criteria were applied: 1) insufficient accelerometer wear time (less than 72 hours) or poor calibration data (n=8,268); 2) missing data in key adjustment variables (n=1,805); 3) previous history of CCD or presence of cardiac implantable electronic devices (n=603); and 4) development of CCD or censoring events that occurred between the baseline assessment and accelerometer measurement (n=502). The final analysis included 92,436 participants (**Supplementary Figure 1**).

Accelerometer-measured 24-hour movement behaviors

The 24-hour movement behaviors were assessed using wrist-worn accelerometer (Axivity AX3; Axivity Ltd., York, UK) data collected over 7 days. The accelerometer recorded data at a frequency of 100 Hz with a measurement range of ±8 g. The raw data were calibrated against local gravitational forces, and noise was filtered out before being segmented into 5-second epochs for analysis. Periods of inactivity lasting ≥60 minutes, where the standard deviation across all three axes was less than 13.0 mg, were classified as non-wear time. Data were processed using established methods, following the validated machine-learning algorithms developed by Doherty et al.,17) which have demonstrated high accuracy (88%) and reliability (Cohen's kappa 0.80) in distinguishing various activity behaviors.18) Specifically, sleep was defined as non-waking behavior; sedentary behavior as waking behavior at ≤1.5 metabolic equivalents of task (METs) in a sitting, lying, or reclining posture; LIPA as waking behavior at <3 METs that does not meet the criteria for sedentary behavior; and MVPA as all activities ≥3 METs.

Covariates

Demographic, socioeconomic, anthropometric, medical, and lifestyle factors were obtained from the baseline assessment. A history of hypertension, diabetes mellitus, dyslipidemia, coronary heart disease, heart failure (HF), atrial fibrillation (AF), and aortic stenosis (AS) or prior aortic valve replacement (AVR) were analyzed based on the medical claims data with International Classification of Diseases, 10th Revision (ICD-10) codes and OPCS Classification of Intervention and Procedures Version 4 (OPCS4) codes and information from questionnaires on disease history (**Supplementary Table 1**). Ethnicity was determined through a series of branching questions regarding ethnic background, and the participants were categorized into 2 main groups: British White (major group) and other ethnicities (minor groups), including Black, Asian, Mixed, other White, Chinese, and other ethnic groups. Smoking status and alcohol consumption were assessed using a touchscreen questionnaire. The Townsend deprivation index was measured as a surrogate for socioeconomic deprivation. The use of heart rate-lowering drugs (beta-blockers, non-dihydropyridine calcium channel blockers, digitalis, and antiarrhythmic drugs) was ascertained through self-reports at the baseline assessment as well as prescription information extracted from linked general practitioner electronic health record data.

Outcomes

Using the ICD-10 and OPCS4 codes applied to hospital inpatient admission data and death registry data provided by the UK Biobank, we extracted outcomes data (**Supplementary Table 2**). The primary outcome was the newly diagnosed CCD, which included first-degree atrioventricular (AV) block, second- or third-degree AV block, fascicular blocks (left anterior, left posterior, right, bifascicular, and trifascicular), bundle branch blocks (right and left), and nonspecific intraventricular block. Secondary outcomes were defined as: 1) newly diagnosed second- or third-degree AV block, and 2) the composite endpoint of newly diagnosed second- or third-degree AV block and concurrent/subsequent pacemaker implantation. The cohorts were followed up until the occurrence of the outcome or the end of the follow-up period, whichever came first (England and Scotland: March 31, 2021; Wales: February 28, 2018).

Electrocardiogram parameters assessment for subgroup analysis

An additional subgroup analysis on an interval-based 12-lead electrocardiogram[19)] was performed to provide mechanistic insight. The electrocardiogram measurements were obtained median 1.9 years (IQR: 0.5–3.2) after the accelerometer assessment. The analysis included measures of P-wave duration, PQ interval, QRS duration, QT duration, corrected QT duration, P-P interval, and R-R interval, which were available for 9,918 participants. Based on previous research,[20)] the heart rate dependency of the PQ interval, we calculated the normalized PQ interval (PQ interval [msec]/R-R interval [sec]) to assess cardiac conduction function. **Supplementary Data 1** contain detailed information on the acquisition of electrocardiogram parameters.

Statistical analysis

The baseline characteristics of the patients were compared using descriptive statistics and are presented as median (IQR) values for continuous variables and numbers (%) for categorical variables. To evaluate the association between 24-hour movement behaviors and newly diagnosed CCD, we conducted multivariable-adjusted Cox regression analysis. The model was adjusted for age, sex, body mass index (BMI), ethnicity, Townsend deprivation index, educational attainment, employment status, smoking status, alcohol consumption, and the presence of CVDs. To assess potential nonlinearity in the relationship between each of the 24-hour movement behaviors and primary outcome, we used restricted cubic splines, selecting the number of knots based on the Bayesian information criterion. Sleep and sedentary behavior did not show significant evidence of nonlinearity (p for nonlinearity=0.490 and 0.307, respectively) and were therefore modeled using linear terms. We further performed compositional data analysis using log-ratio pivot coordinates, which are appropriate for analyzing the compositional nature of the 24-hour movement behaviors. The log-ratio approach uses log-transformed ratios to describe compositional data.[21)] Specifically, we applied isometric log-ratio (ILR) pivot coordinates, a widely used and validated method, to estimate the effects of reallocating time among the 24-hour movement behaviors.[18)22)] To account for the relative impact of one behavior on the others, we provide the coefficients of the first ILR pivot coordinates. The proportional hazard assumption was assessed using Schoenfeld residuals, and no violation was observed.[23)] We performed an additional compositional data analysis on an interval-based 12-lead electrocardiogram[19)] using multivariable-adjusted linear regression to examine associations of the 24-hour movement behaviors with electrocardiogram parameters.

We conducted sensitivity analyses, which included: 1) competing risks attributable to death resulting from any causes, addressed using a cause-specific hazard ratio (HR) for which mortality was censored at the date of death, according to Fine and Gray,[24)] 2) excluding participants who had heart-rate lowering drugs prescribed before or after follow-up, 3) excluding participants with less than 5 years of follow-up after the accelerometer measurement, and 4) excluding participants with AF, AS or AVR, myocardial infarction (MI), or HF either at baseline or during follow-up. Statistical significance was set at $p<0.05$. Statistical analyses were performed using R software (version 4.1.2; R Foundation, www.R-project.org, Vienna, Austria).

RESULTS

Baseline characteristics

The baseline characteristics of the study cohort are outlined in **Table 1**, and a comparison of these characteristics with those of the excluded participants is shown in **Supplementary Table 3**. The final cohort comprised 92,436 participants with valid accelerometer data. The median age of the participants was 58 years (IQR: 50–63), and 54% were female. The median BMI was 26 kg/m^2 (IQR: 23.6–28.9). Participants aged 60 years and older, those who were female, those who were unemployed, those with lower education levels, current smokers, those who had high BMI, and those with a history of CVD had a relatively lower MVPA composition than other groups (**Supplementary Table 4**). The median daily composition of movement behaviors in the study cohort was 8.7 hours of sleep, 9.4 hours of sedentary behavior, 5.0 hours of LIPA, and 34 minutes of MVPA. This composition is shown in **Supplementary Figure 2**.

Association of each movement behavior and outcomes

During a median follow-up of 6.1 years (IQR: 5.6–6.6), a total of 1,442 cases of newly diagnosed CCD occurred (2.58 per 1,000 person-years). Regarding the secondary outcomes, a total of 313 cases of newly diagnosed second- or third-degree AV block were observed (0.56 per 1,000 person-years). Additionally, 261 cases of pacemaker implantation occurred during the study period (0.47 per 1,000 person-years). In the independent multivariable-adjusted Cox regression analysis of each of the four behaviors, MVPA was significantly associated with a reduced risk of CCD (HR, 0.83; 95% confidence interval [CI], 0.75–0.92) and second- or third-degree AV block (HR, 0.80; 95% CI, 0.65–0.98). Specifically, MVPA duration of 42 minutes (0.7 hours) or more per day was associated with a statistically significant reduction in CCD risk. The association between MVPA and pacemaker implantation, while not statistically significant, also showed a similar trend towards reduced risk (HR, 0.80; 95% CI, 0.64–1.01). Sedentary behavior was significantly associated with an increased risk of CCD (HR, 1.05; 95% CI, 1.02–1.08) and second- or third-degree AV block (HR, 1.19; 95% CI, 1.02–1.40). Sedentary behavior exceeding 563 minutes (9.4 hours) per day was associated with a statistically

Table 1. Composition of 24-hour movement behaviors according to study participants

Variables	Participants	Time spent in movement behaviors (hour/day)			
		Sleep	Sedentary	LIPA	MVPA
Overall	92,436 (100.0)	8.7 (8.0–9.5)	9.4 (8.2–10.6)	5.0 (3.9–6.1)	0.6 (0.3–1.0)
Age range at baseline assessment (years)					
40–49	20,697 (22.4)	8.6 (7.9–9.3)	9.5 (8.2–10.8)	4.9 (3.9–6.2)	0.6 (0.3–1.0)
50–59	33,025 (35.7)	8.7 (8.0–9.5)	9.3 (8.1–10.5)	5.0 (4.0–6.2)	0.6 (0.3–1.0)
≥60	37,714 (41.9)	8.8 (8.1–9.6)	9.4 (8.2–10.5)	4.9 (3.9–6.0)	0.5 (0.3–0.9)
Age range at accelerometer wearing (years)					
40–49	7,899 (8.5)	8.6 (7.9–9.3)	9.5 (8.2–10.7)	5.0 (3.9–6.2)	0.6 (0.3–1.0)
50–59	26,786 (28.9)	8.6 (7.9–9.4)	9.5 (8.2–10.7)	4.9 (3.9–6.1)	0.6 (0.3–1.0)
≥60	57,751 (62.5)	8.8 (8.1–9.6)	9.3 (8.2–10.5)	5.0 (3.9–6.1)	0.5 (0.3–0.9)
Sex					
Female	52,012 (56.3)	8.8 (8.1–9.5)	9.1 (7.9–10.2)	5.3 (4.3–6.4)	0.5 (0.2–0.8)
Male	40,424 (43.7)	8.7 (7.9–9.5)	9.8 (8.6–11.0)	4.5 (3.5–5.6)	0.7 (0.4–1.2)
Ethnicity					
Minor group	8,298 (9.0)	8.6 (7.9–9.4)	9.4 (8.1–10.7)	5.0 (3.9–6.3)	0.6 (0.3–1.0)
Major group	84,138 (91.0)	8.7 (8.1–9.5)	9.4 (8.2–10.6)	4.9 (3.9–6.1)	0.6 (0.3–1.0)
Townsend deprivation index					
Least deprived (<−3.82)	23,099 (25)	8.8 (8.1–9.5)	9.3 (8.1–10.5)	5.0 (4.0–6.1)	0.6 (0.3–1.0)
2nd least deprived (−3.82 to −2.45)	23,144 (25)	8.8 (8.1–9.5)	9.3 (8.1–10.5)	5.0 (4.0–6.1)	0.6 (0.3–1.0)
2nd most deprived (−2.45 to −0.21)	23,071 (25)	8.7 (8.1–9.5)	9.4 (8.1–10.6)	5.0 (3.9–6.1)	0.6 (0.3–1.0)
Most deprived (>−0.21)	23,122 (25)	8.7 (7.9–9.5)	9.5 (8.3–10.8)	4.8 (3.8–6.0)	0.6 (0.3–1.0)
Employment status					
Unemployed	34,790 (37.6)	8.8 (8.2–9.7)	9.2 (8.1–10.4)	5.0 (4.0–6.1)	0.5 (0.2–0.9)
Employed	57,646 (62.4)	8.6 (8.0–9.4)	9.5 (8.2–10.7)	4.9 (3.9–6.1)	0.6 (0.3–1.0)
Education					
None of below	7,561 (8.2)	9.0 (8.2–9.9)	9.1 (7.8–10.3)	5.1 (4.0–6.2)	0.4 (0.2–0.8)
School leaver	22,620 (24.5)	8.8 (8.1–9.6)	9.2 (7.9–10.4)	5.2 (4.1–6.4)	0.5 (0.2–0.9)
Further education	21,830 (23.6)	8.7 (8.0–9.5)	9.3 (8.1–10.5)	5.0 (3.9–6.1)	0.5 (0.3–0.9)
Higher education	40,425 (43.7)	8.6 (8.0–9.4)	9.6 (8.4–10.8)	4.8 (3.8–5.9)	0.7 (0.4–1.1)
Current tobacco smoking					
Never or ex-smoker	88,221 (95.4)	8.7 (8.0–9.5)	9.4 (8.2–10.6)	5.0 (3.9–6.1)	0.6 (0.3–1.0)
Current	4,215 (4.6)	8.8 (8.0–9.7)	9.6 (8.3–10.9)	4.8 (3.7–6.0)	0.4 (0.2–0.8)
Alcohol intake frequency					
Never	7,399 (8.0)	8.7 (8.0–9.5)	9.4 (8.1–10.6)	5.0 (3.9–6.2)	0.6 (0.3–1.0)
Special occasions only	10,829 (11.7)	8.7 (8.0–9.5)	9.4 (8.2–10.6)	4.9 (3.9–6.1)	0.6 (0.3–1.0)
One to three times a month	10,218 (11.1)	8.7 (8.0–9.5)	9.3 (8.1–10.6)	5.0 (4.0–6.1)	0.6 (0.3–1.0)
Once or twice a week	23,886 (25.8)	8.7 (8.0–9.5)	9.4 (8.2–10.6)	4.9 (3.9–6.1)	0.6 (0.3–1.0)
Three or four times a week	21,214 (22.9)	8.7 (8.0–9.5)	9.4 (8.2–10.6)	5.0 (3.9–6.1)	0.6 (0.3–1.0)
Daily or almost daily	18,890 (20.4)	8.7 (8.0–9.5)	9.4 (8.2–10.6)	5.0 (3.9–6.1)	0.6 (0.3–1.0)
Body mass index (kg/m^2)					
Underweight (<18.5)	527 (0.6)	8.6 (8.0–9.4)	8.6 (7.4–9.8)	5.7 (4.4–6.9)	0.7 (0.4–1.2)
Normal (18.5 to 24.9)	36,362 (39.3)	8.7 (8.1–9.5)	9.0 (7.9–10.2)	5.2 (4.2–6.4)	0.7 (0.4–1.1)
Overweight (25.0 to 29.9)	38,202 (41.3)	8.7 (8.0–9.5)	9.5 (8.3–10.7)	4.9 (3.9–6.0)	0.6 (0.3–1.0)
Obese (>30.0)	17,345 (18.8)	8.7 (7.9–9.6)	10.0 (8.7–11.2)	4.6 (3.6–5.7)	0.4 (0.2–0.7)
History of CVD*					
No	64,476 (69.8)	8.7 (8.0–9.5)	9.3 (8.1–10.5)	5.0 (4.0–6.2)	0.6 (0.3–1.0)
Yes	27,960 (30.2)	8.8 (8.1–9.6)	9.6 (8.4–10.8)	4.8 (3.7–5.9)	0.5 (0.2–0.9)

Values are presented as number (%) or median (interquartile range).

CVD = cardiovascular disease; LIPA = light-intensity physical activity; MVPA = moderate-to-vigorous intensity physical activity.

*CVD was defined as the presence of any of the following at baseline: hypertension, diabetes mellitus, dyslipidemia, ischemic stroke, coronary heart disease, or heart failure.

significant increase in CCD risk. The association between sedentary behavior and pacemaker implantation, while not statistically significant, also showed a similar trend towards increased risk (HR, 1.16; 95% CI, 0.97–1.38). Sleep and LIPA showed no statistically significant associations with any of the outcomes (**Figures 1** and **2**).

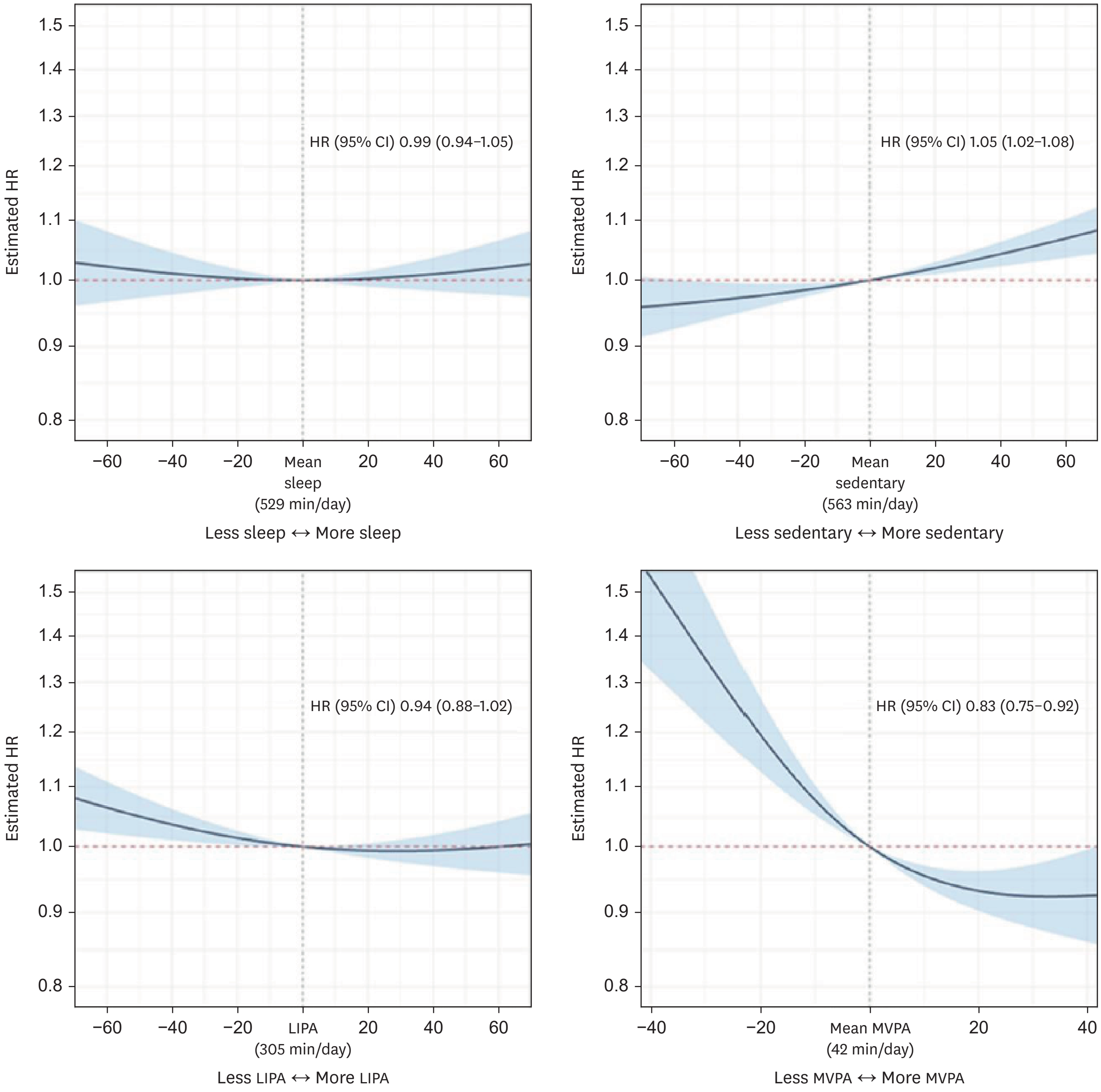

Figure 1. Risk of CCD according to continuous changes in individual 24-hour movement behaviors (sleep, sedentary behavior, LIPA, MVPA).
CCD = cardiac conduction disease; CI = confidence interval; HR = hazard ratio; LIPA = light-intensity physical activity; MVPA = moderate-to-vigorous intensity physical activity.

Impact of movement behavior reallocation on outcomes

We estimated the following results based on the mean movement behavior composition of study participants (mean sleep time: 529 minutes/day, mean sedentary time: 563 minutes/day, mean LIPA time: 305 minutes/day, mean MVPA time: 42 minutes/day). In time reallocation analysis, a greater reallocation of time to MVPA from other behaviors (sleep, sedentary behavior, or LIPA) was associated with a lower risk of CCD (**Figure 3A**) and reallocation to sedentary behavior from other behaviors (sleep, LIPA, or MVPA) was

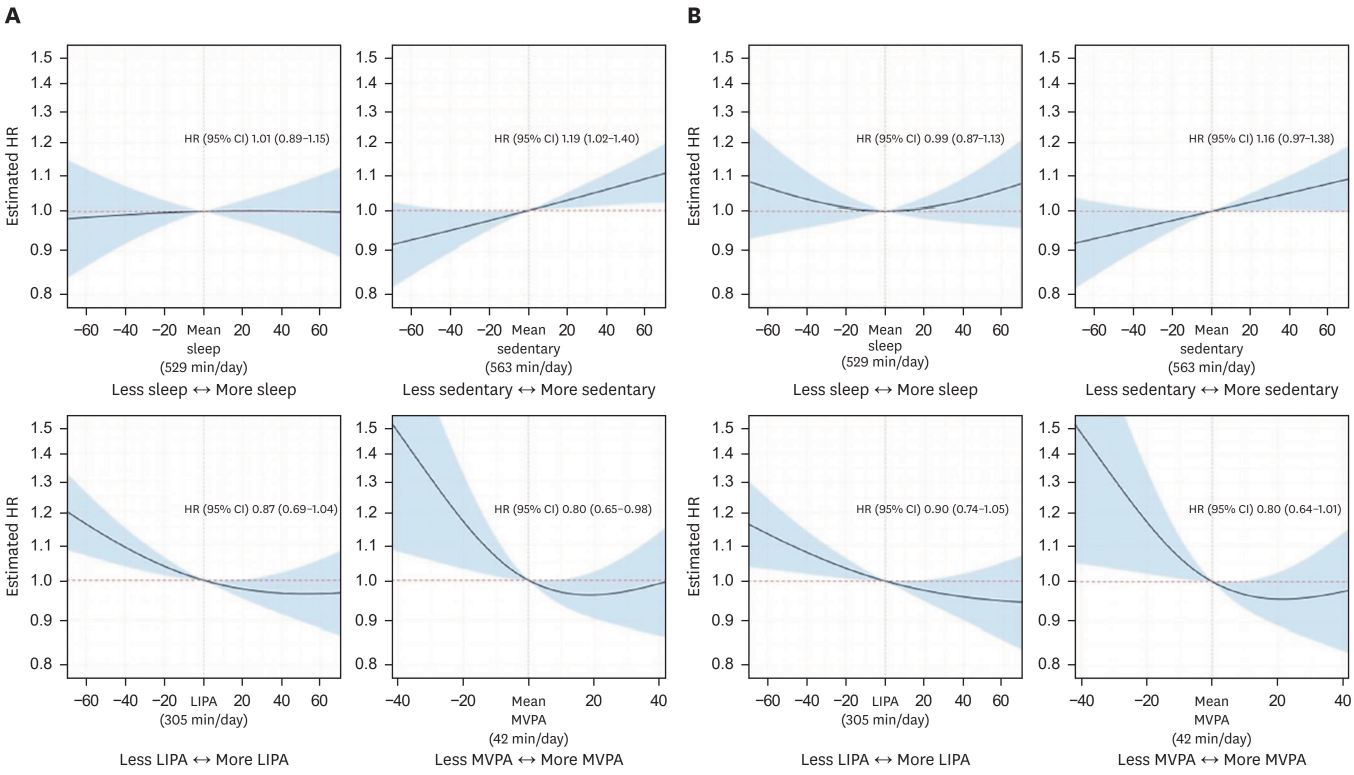

Figure 2. Risk of second- or third-degree atrioventricular block (A) and pacemaker implantation (B) according to continuous changes in individual 24-hour movement behaviors (sleep, sedentary behavior, LIPA, MVPA).
CI = confidence interval; HR = hazard ratio; LIPA = light-intensity physical activity; MVPA = moderate-to-vigorous intensity physical activity.

associated with a higher risk of CCD (**Figure 3B**). Reallocating 30 minutes from sleep, sedentary behavior, or LIPA to MVPA was associated with a reduction in the risk of CCD, with HRs (95% CI); 0.95 (0.92–0.98), 0.94 (0.91–0.98), and 0.96 (0.93–1.00), respectively. Conversely, reallocating 30 minutes from sleep, LIPA, or MVPA to sedentary behavior was associated with an increased risk, with HRs (95% CI); 1.01 (0.98–1.03), 1.02 (1.00–1.03), and 1.12 (1.05–1.19), respectively. Similar patterns of association were observed for the secondary outcomes (second- or third-degree AV block in **Supplementary Figure 3** and pacemaker implantation in **Supplementary Figure 4**). No significant associations were observed between reallocations involving sleep and LIPA in relation to risk of outcomes (**Supplementary Figures 5**-**7**).

We also examined the associations of replacing time in the combined composition of other movement behaviors with time in each specific behavior with all movement behaviors mutually adjusted within the 24-hour period (**Figure 4**). Reallocating 30 mins/day to MVPA from other behaviors (sleep, sedentary behavior, and LIPA) was associated with a 4% lower risk of CCD (HR, 0.96; 95% CI, 0.93–0.98). In contrast, reallocating 30 mins/day to sedentary behavior from other behaviors (sleep, LIPA, and MVPA) was associated with a 3% higher risk (HR, 1.03; 95% CI, 1.01–1.05). Shifting 30 mins/day to sleep or LIPA from other behaviors did not show a significant association for CCD risk. For the secondary outcomes (second- or third-degree AV block and pacemaker implantation), similar trends were observed as for CCD (**Supplementary Figures 8** and **9**).

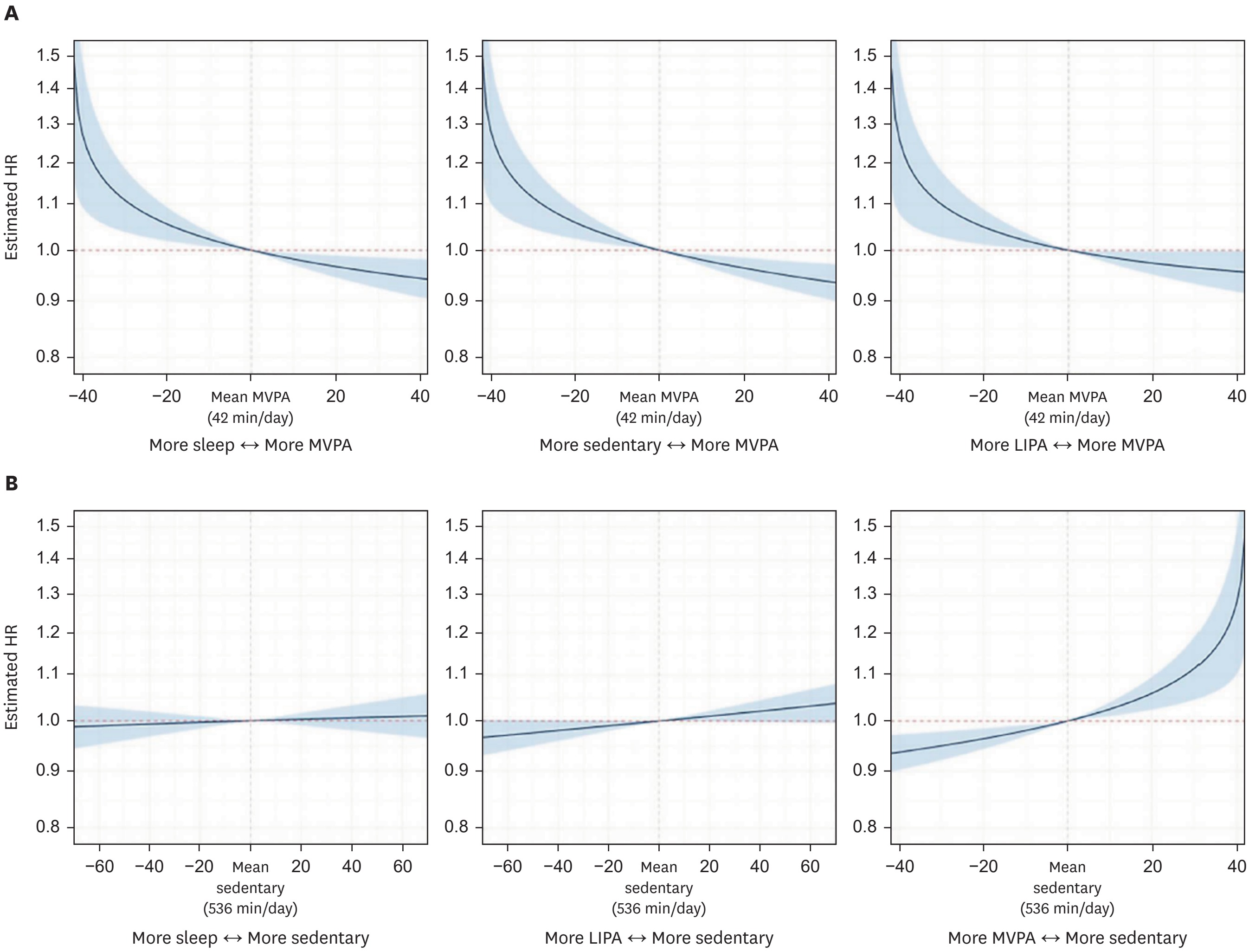

Figure 3. Risk of CCD with time reallocation among 24-hour movement behavior. (A) Risk when reallocating time from sleep/sedentary/LIPA with MVPA, (B) Risk when reallocating time from sleep/LIPA/MVPA with sedentary behavior.
CCD = cardiac conduction disease; HR = hazard ratio; LIPA = light-intensity physical activity; MVPA = moderate-to-vigorous intensity physical activity.

Impact of movement behavior reallocation on electrocardiographic parameter

In a subgroup analysis of participants with interval-based 12-lead electrocardiogram, we investigated the association between 24-hour movement behaviors and electrocardiographic parameters using compositional data analysis. A greater reallocation of time to MVPA from other behaviors was significantly associated with a decrease in the normalized PQ interval (β coefficient, −1.67; 95% CI, −2.33 to −1.00), whereas reallocation to sedentary behavior from other behaviors was associated with a significant increase in the normalized PQ interval (β coefficient, 2.27; 95% CI, 0.98 to 3.57) (**Supplementary Table 5**). Reallocation plots are shown in **Supplementary Figures 10-13**.

Sensitivity analysis

In sensitivity analyses (**Supplementary Table 6**), we conducted the following: 1) using a Fine-Gray model accounting for all-cause death as a competing event, 2) excluding participants prescribed heart-rate lowering drugs including antiarrhythmic drugs either before or during follow-up, 3) excluding participants with less than 5 years of follow-up post-accelerometer

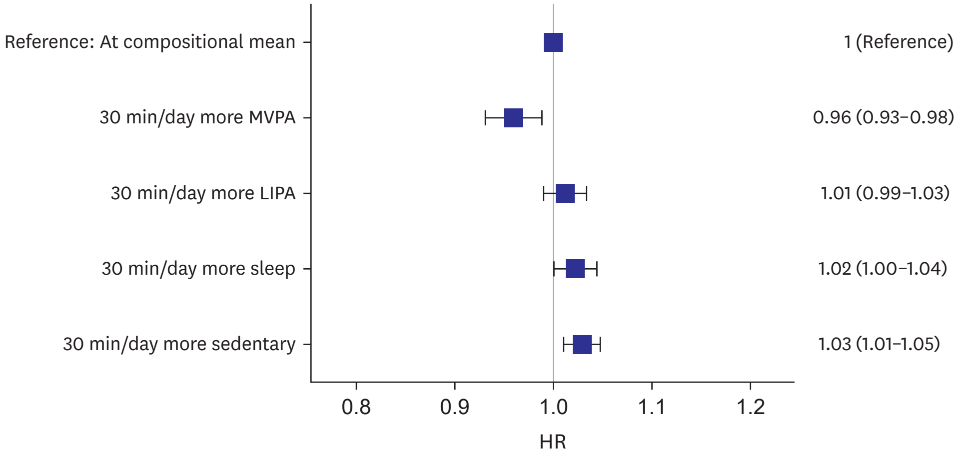

Figure 4. HRs for CCD with 30-minute reallocations among 24-hour movement behaviors. Forest plot illustrates the effects of reallocating time from all other combined behaviors to a specific behavior based on compositional means (sleep: 529 minutes, sedentary: 563 minutes, LIPA: 305 minutes, MVPA: 42 minutes).
CCD = cardiac conduction disease; HR = hazard ratio; LIPA = light-intensity physical activity; MVPA = moderate-to-vigorous intensity physical activity.

measurement, and 4) excluding participants diagnosed with AF, AS/AVR, MI, or HF either at baseline or during follow-up. Results remained consistent throughout sensitivity analyses. Furthermore, stratified analyses based on BMI, sex, and guideline-recommended MVPA levels (≥150 minutes/week of MVPA) yielded no significant interactions (p for interaction=0.130, 0.681, and 0.365, respectively).

DISCUSSION

In this large prospective cohort study of 92,436 participants, we used wrist-worn accelerometer data that allowed for a more precise measurement of PA and their impact on the cardiac conduction system. Our main findings revealed that greater time spent in MVPA was significantly reduced risk of CCD, while higher volumes of sedentary behavior were associated with an increased risk. These directional associations generally remained those observed for the secondary outcomes, including second- or third-degree AV block and pacemaker implantation. Furthermore, time reallocation analysis corroborated these findings, indicating that replacing time in other behaviors with MVPA was associated with lower risk, while replacing time with sedentary behaviors was associated with higher risk. We also found that specific behaviors were associated with changes in electrocardiographic parameters, such as the normalized PQ interval. These findings underscore the distinct impact of different movement behaviors on cardiac conduction health.

Our study provides a novel perspective on the growing body of literature regarding PA and its relationship with CCD, particularly by employing objective accelerometer data and a compositional data analysis approach. A previous study,13) which also used UK Biobank data but relied on self-reported physical activity levels, assessed the association between PA and bradyarrhythmia, concluding no significant association between the total PA and bradyarrhythmia risk. In contrast, the present study used wrist-worn accelerometers data, providing more accurate 24-hour movement behavior data and an objective assessment of PA intensity and duration. This methodology enabled a more detailed analysis of time spent in different movement behaviors and the effects of their redistribution across 24-hours day. Leveraging these methodological advantages, we identified significant associations between higher volumes of MVPA and reduced risk of CCD, suggesting a protective association of MVPA.

We found that a greater volume of time spent in sedentary behaviors was significantly associated with an increased risk of CCD. This finding highlights the potential benefits of promoting a more active lifestyle and specifically reducing sedentary behavior time to mitigate the risk of cardiac conduction abnormalities. Prolonged sedentary behavior and physical inactivity have been well documented as risk factors for various CVDs, emphasizing the importance of interventions that encourage more dynamic activities throughout the day.25) Our findings thus reinforce the value of increasing engaging in active behaviors and reducing sedentary time to optimize cardiovascular health.

Several underlying mechanisms could potentially explain the observed associations between movement behaviors and cardiac conduction health. Regular PA is associated with numerous physiological adaptations that confer cardiac protection and may specifically benefit the cardiac conduction system. At the cellular and molecular levels, PA induces resistance to ischemic reperfusion injury, reduces oxidative damage, and prevents myocardial fibrosis by modulating various signaling pathways.26-28) PA also promotes beneficial cardiac remodeling and improves cardiometabolic risk factors, such as weight management and insulin sensitivity, which are crucial for protecting cardiac conduction function.4)29)30) Conversely, prolonged sedentary behavior exerts detrimental effects through pathways involving endothelial dysfunction, metabolic dysfunction, and oxidative stress. Such changes, along with potential impacts on cardiac fibrosis and calcium handling, may contribute to electrical instability and impaired cardiac conduction system, increasing the risk of CCD.25)

We further explored the relationship between 24-hour movement behaviors and electrocardiographic phenotype using the normalized PQ intervals, which account for the heart rate dependency of the PQ interval.20) This analysis revealed that a greater volume of sedentary behavior was significantly associated with longer normalized PQ intervals, while higher volumes of MVPA were significantly associated with shorter normalized PQ intervals, further highlighting the potential impact of these behaviors on cardiac conduction system.

This study has several important limitations. First, ascertainment of baseline CCD relied on self-report or diagnostic codes from medical claims and registries, without baseline electrocardiogram verification. This approach may have resulted in misclassification of some cases, as individuals with undiagnosed CCD at baseline may have been included in the seemingly healthy cohort. Second, the UK Biobank data may introduce selection bias, as participants tend to be healthier and predominantly of the white ethnicity. This homogeneity makes it difficult to generalize the findings to other populations or ethnic groups. Additionally, potential detection bias should be considered. Individuals with higher sedentary behavior or lower overall physical activity may have greater healthcare contact, leading to increased opportunities for the diagnosis of subclinical or asymptomatic outcomes. Third, as with any observational study, the ability to infer causality is limited. Individuals with better overall health status may naturally engage in higher levels of MVPA, while those with underlying illness or preclinical CCD may be more sedentary. This bidirectional relationship could bias the observed associations. Fourth, while the study utilized open-source machine learning methods to classify movement behaviors, the accuracy of these classifications, although high (88% accuracy, kappa 0.80),18) may still leave room for misclassification. Fifth, the reliance on short-term accelerometer data may not accurately reflect individuals' long-term or life-course behavior patterns. Sixth, using mean values as a reference in compositional data analysis can obscure individual variability. Seventh, although we conducted robust sensitivity analyses and adjusted for a wide range of covariates, residual confounding remains a potential concern.

In conclusion, this large-scale prospective study using objective accelerometer data and compositional data analysis highlights the distinct associations of 24-hour movement behaviors with CCD risk. Our findings demonstrate that greater time spent in MVPA is associated with a lower risk of CCD, whereas prolonged sedentary behavior significantly is associated with a higher risk. These associations were consistently observed across primary and secondary outcomes, and were further supported by electrocardiographic parameters. These results provide critical insights into how daily movement behaviors are associated with cardiac conduction health, reinforcing the importance of increasing active time and reducing sedentary time in public health guidelines.

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SUPPLEMENTARY MATERIALS

Supplementary Data 1

Electrocardiogram parameters acquisition and measurement

Supplementary Table 1

Definitions used for defining comorbidities

Supplementary Table 2

Definitions used for defining the outcomes

Supplementary Table 3

Comparisons between inclusion versus exclusion subjects who have usable accelerometer dataset

Supplementary Table 4

Baseline characteristics across quartiles of moderate-to-vigorous physical activity time

Supplementary Table 5

Linear regression* of first isometric log-ratio pivot coordinate for electrocardiography parameters by each movement behavior using compositional data (n=9,918)

Supplementary Table 6

Cox regression coefficients of first isometric log-ratio pivot coordinate for outcomes of each movement behavior using compositional data

Supplementary Figure 1

Flowchart of the study participants.

Supplementary Figure 2

Distribution of 24-hour movement behaviors. (A) Density plots of sleep, sedentary behavior, and PA combines LIPA and MVPA. (B) Ternary plot of 24-hour movement behaviors distribution among sleep, sedentary behavior, and PA as percentages of total daily time. Contour lines indicate the 25, 50%, and 75% data density, with darker regions representing higher densities.

Supplementary Figure 3

Risk of second- or third-degree atrioventricular block with time reallocation among 24-hour movement behavior. (A) Risk when reallocating time from sleep/sedentary/LIPA with MVPA, (B) Risk when reallocating time from sleep/LIPA/MVPA with sedentary behavior.

Supplementary Figure 4

Risk of pacemaker implantation with time reallocation among 24-hour movement behavior. (A) Risk when reallocating time from sleep/sedentary/LIPA with MVPA, (B) Risk when reallocating time from sleep/LIPA/MVPA with sedentary behavior.

Supplementary Figure 5

Risk of CCD with time reallocation among 24-hour movement behavior. (A) Risk when reallocating time from sleep/sedentary/MVPA with LIPA, (B) Risk when reallocating time from sedentary/LIPA/MVPA with sleep.

Supplementary Figure 6

Risk of second- or thrid-degree AV block with time reallocation among 24-hour movement behavior. (A) Risk when reallocating time from sleep/sedentary/MVPA with LIPA, (B) Risk when reallocating time from sedentary/LIPA/MVPA with sleep.

Supplementary Figure 7

Risk of pacemaker implantation with time reallocation among 24-hour movement behavior. (A) Risk when reallocating time from sleep/sedentary/MVPA with LIPA, (B) Risk when reallocating time from sedentary/LIPA/MVPA with sleep.

Supplementary Figure 8

HRs for second- or thrid-degree AV block with 30-minute reallocations among 24-hour movement behaviors. Forest plot illustrates the effects of reallocating time from all other combined behaviors to a specific behavior based on compositional means (sleep: 529 minutes, sedentary: 563 minutes, LIPA: 305 minutes, MVPA: 42 minutes).

Supplementary Figure 9

HRs for pacemaker implantation with 30-minute reallocations among 24-hour movement behaviors. Forest plot illustrates the effects of reallocating time from all other combined behaviors to a specific behavior based on compositional means (sleep: 529 minutes, sedentary: 563 minutes, LIPA: 305 minutes, MVPA: 42 minutes).

Supplementary Figure 10

Change in the normalized PQ interval with time reallocation from each behavior to MVPA.

Supplementary Figure 11
Change in the normalized PQ interval with time reallocation from each behavior to sedentary behavior.

Supplementary Figure 12
Change in the normalized PQ interval with time reallocation from each behavior to LIPA.

Supplementary Figure 13
Change in the normalized PQ interval with time reallocation from each behavior to sleep.

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