This article has been accepted for publication in JECH following peer review.

The definitive copyedited, typeset version is available online at

10.1136/jech-2025-225231

24-hour Physical Activity, Sedentary Behaviour, and Sleep Profiles in Individuals with Cancer: A UK Biobank Cohort Study

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***Keywords*:** physical activity, exercise, sedentary behaviour, sitting time, sleep, cancer, compositional data analysis, cohort studies

Abstract

Background

Behaviours across a 24-hour day, including physical activity, sedentary time, and sleep, are disrupted following cancer and contribute to cancer-related outcomes. This study describes the day-to-day 24-hour behaviour profiles of individuals with and without cancer, considering time since diagnosis and cancer types.

Methods

Seven days of accelerometer data from the UK Biobank ($M \pm SD_{age}$=62.3±7.9y; 56.4% female) were derived from machine learning models to assess the 24-hour behaviours in individuals with cancer (n=10152; $M \pm SD_{years\ since\ diagnosis}$=7.4±6.1y) compared to healthy (free of diseases) individuals (n=13722). Diagnoses were identified using ICD-10 codes within cancer registries. Bayesian compositional data analysis compared profiles between individuals with and without cancer, across time since diagnosis (<1y, 1-5y, >5y) and 14 cancer types.

Results

The least physically active profiles were observed for those with <1 year since cancer diagnosis and in cancers with poor prognoses. Compared to healthy individuals, those with <1 year since cancer diagnosis had 40 min/day less physical activity (light plus moderate-to-vigorous intensities), compensated by 40 min/day more inactive time (sedentary plus sleep periods). Differences also varied across cancer types, ranging from 22-75 min/day less physical activity and 22-75 min/day more inactive time, between individuals with cancers and healthy individuals. Cancers with poorer prognoses (e.g., lung, gastrointestinal tract) had the least optimal profiles, whereas cancers with better prognoses (e.g., prostate, skin) showed profiles closer to healthy individuals.

Conclusion

The 24-hour behaviour profiles differed by cancer history, prognosis, and type. Supporting a healthy balance of behaviours, that can feasibly be achieved within a 24-hour day, should be considered for cancer survivors, particularly in the year after diagnosis and in poor prognosis cancers.

What is already known on this topic

- Behaviours across a 24-hour period, including physical activity, sedentary behaviour, and sleep are disrupted following cancer and contribute to cancer-related outcomes.

What this study adds

- Adults with cancer have less healthy day-to-day 24-hour behaviour profiles than healthy adults, with 25 min/day trade-offs between physically active and inactive time (↓ 11 min/day in moderate-to-vigorous and ↓ 14 min/day in light physical activity, compensated by ↑ 11 min/day in sedentary behaviour and ↑ 14 min/day in sleep period).
- The least physically active profiles were observed for those with <1 year since cancer diagnosis (up to 40 min/day less physical activity) and in cancers with poor prognoses (up to 75 min/day less physical activity).

How this study might affect research, practice or policy

- Guidelines and interventions for cancer survivors should move towards a healthy daily balance of 24-hour behaviours.
- Increased 25 min/day physical activity at the expense of inactive time may be recommended for cancer survivors.
- Support should further be allocated for survivors in the year after diagnosis and in poor prognosis cancers.

Introduction

Cancer is the second leading cause of death worldwide[1], and annual incidence rates are projected to increase by 47% for the next two decades[2]. Simultaneously, an ageing population and longer survival times are resulting in a growing population of cancer survivors[3]. Physical inactivity is a major risk factor for comorbidities[4 5], cancer recurrence[6], and cancer mortality[6 7]. However, individuals with cancer are reported to engage in less physical activity[8] than healthy individuals throughout all phases of treatment and stages of cancer[9]. Support to achieve and maintain a healthy physical activity level is clearly important for individuals with cancer[8].

Physical activity should not be considered as an independent behaviour. Changing time spent in physical activity requires trade-offs with other behaviours within the 24-hour day. This is because each day consists of exhaustive and mutually exclusive movement-related behaviours that always sum to 24 hours, including moderate-to-vigorous physical activity (MVPA), light physical activity (LPA), sedentary behaviour (SB), and sleep. Among these behaviours, not only physical inactivity[10], but both longer SB[11] and short sleep (<5h)[12] are associated with all-cause mortality in cancer survivors. Accordingly, the distribution of time across behaviours is more relevant than time spent in any single behaviour[13]. For example, an individual who reduces time in MVPA must compensate by spending more time in other behaviours (LPA, SB, and/or sleep); they cannot decrease time in MVPA while keeping time in other behaviours fixed. Understanding how individuals allocate their time across the full spectrum of 24-hour behaviours following a cancer diagnosis is crucial to inform the development of meaningful and targeted behaviour guidelines and interventions that are feasible for this population and fit within the confines of a 24-hour day.

Recent findings from the CHALLENGE trial showed physical activity (structured exercise) improved disease-free and overall survival for colon cancer[14]. However, different types of cancer are not homogeneous in prognoses[1 2], yet the 24-hour behaviour profiles by cancer type are underexplored. No studies have reliably characterised the time allocation of movement behaviours across 24 hours in individuals with cancer, with existing findings relying on self-reported measurements that are limited by recall bias and difficulty in reporting incidental activity. Data from objective assessments, such as accelerometers, can reduce misclassification of physical activity levels

and better guide personalised interventions. In addition, no study has compared 24-hour behaviours of individuals with and without cancer using compositional data analysis (CoDA)[13], a methodological approach that captures the relative information of 24-hour behaviours and allows them to simultaneously be in one model.

This study leverages the large accelerometer dataset from the UK Biobank (UKB) study to systematically describe the 24-hour behaviour profile of individuals with and without cancer. We also evaluate how the 24-hour behaviour profile differs according to time since cancer diagnosis and cancer types. Finally, we examine whether 24-hour behaviour variation across cancer types can be explained by their average 5-year survival rates.

Methods

Study design and participants

The UKB is a population-based, prospective study conducted across the United Kingdom, with approximately 500 000 participants aged 40-69 years recruited in 2006–2010. We used data from a subset of 103 720 participants who provided up to 7-day accelerometer data in 2013–2015[15], with median wear time of 6.9 days. We excluded participants with device calibration or reading errors (>1% values ±8g), implausibly high average acceleration (>100mg), insufficient wear time (<72h) or no wear data in each one-hour period of the 24-hour cycle, and unreliable due to the uncompressed dataset returned by the accelerometer device having unexpectedly large/small size[15 16]. We followed the STROBE guidelines (Supplementary Table S1). Study variables were obtained from UK Biobank database in March 2024 and described in Supplementary Table S4.

Cancer and non-cancer diagnosis ascertainment

Cancer group

Cancer diagnoses were identified using cancer registries from England, Scotland, and Wales. *Cancer* group was defined as individuals with a history of one or more cancer diagnoses by the time of accelerometer measurement. *Time since cancer diagnosis* was calculated as time between the date of the most recent diagnosis and the first day of accelerometer measurement. Given common benchmarks of 1-year and 5-year survival rates, participants were categorised into three groups: <1 year, 1-5 years, and >5 years since cancer diagnosis. We classified 14 common *cancer types* including

Blood, Breast, Colorectal, Endocrine Gland, Gastrointestinal, Genitourinary, Gynaecological, Head and Neck, Lung, Melanoma, Skin (non-melanoma), Prostate, Multiple Primary (more than one type), and Other Cancer (see Supplementary Table S2 for ICD-10 codes). Individual cancer types were chosen based on common cancers identified by Cancer Research UK and the National Cancer Institute, with at least 50 cases in the UKB. Cancer types that are less common and/or contain few participants are categorised as *Other Cancer*, whereas those with more than one primary cancers are categorised as *Multiple Primary*. Participants diagnosed with cancer alongside one or more other non-cancer comorbidities were included in the cancer group, due to high prevalence of multimorbidity in cancer (94% in the current study, consistent with 91% in a previous study[17]).

Non-cancer group

Non-cancer diagnoses were identified using hospital inpatient records, self-reports, primary care, and death registers. Diagnoses were collated into 11 chronic conditions defined according to International Classification of Diseases (ICD-10) Chapters (see Supplementary Table S3 for ICD-10 codes) and were previously found to be associated with physical activity[18]. Two non-cancer groups were defined, 1) *Healthy* as no clinical diagnosis up to 1 year after accelerometer measurement, and 2) *Other Conditions* as one or more diagnoses (except cancer) at the time of accelerometry.

Prognoses (survival rates) by cancer type

Age-standardised, 5-year survival data for different cancers were extracted from the Cancer Research UK population-based surveillance. Survival rates for our categories (*Blood, Breast, Colorectal, Endocrine Gland, Gastrointestinal, Genitourinary, Gynaecological, Head and Neck, Lung, Melanoma, Prostate*) were calculated as the weighted average survival across included cancers and cases per UK nation (England, Scotland, Wales).

24-hour behaviour assessment

MVPA, LPA, SB, and sleep period were derived from the Axivity AX3 wrist-worn triaxial accelerometers. MVPA, LPA, and SB were defined using intensity in metabolic equivalent of task (METs), whereas sleep period was defined as non-waking behaviour[16]. Participants were instructed to wear the device on their dominant wrist continuously for seven days. The accelerometers captured three-dimensional acceleration data at 100Hz with a dynamic range of ±8g. Accelerometer data were

extracted and processed using methods described previously[15]. Missing time due to non-wear was imputed by averaging the behaviour in the corresponding times across valid days[15]. Times spent in behaviours were calculated using random forest and hidden Markov models, developed and validated against wearable camera and sleep diary reference measurements in ~150 adults[16]. Data were averaged across available days to obtain typical daily 24-hour behavioural profile, as weekday-weekend and season differences were minimal[15]. Zero values (0 minute in a behaviour) were imputed using Expectation-Maximisation algorithms[19].

Statistical analyses

Analyses were performed in R using Bayesian compositional data analysis[13 20 21]. Here, the raw 4-part composition of the 24-hour behaviours (MVPA, LPA, SB, and sleep period), were expressed as a set of three *isometric log ratio* (*ilr)* coordinates for model estimation. This *ilr* transformation, using a sequential binary partition, prevents the perfect multicollinearity associated with fitting raw compositional data.

To determine how 24-hour behaviour profiles differ by time since cancer diagnosis, a Bayesian multivariate model (a) was fitted with the *ilr* coordinates representing 24-hour behaviour outcomes and *time since cancer diagnosis* predictor (5 categories including 3 cancer groups [<1 year, 1-5 years, >5 years], 2 non-cancer groups [*Other Conditions* and *Healthy*]). Time in 24-hour behaviours for everyone with cancer was calculated as weighted average of the three cancer groups. Post-hoc contrasts estimated the differences in 24-hour behaviours in cancer groups (by time since cancer diagnosis) compared to the two non-cancer groups. Two methods of contrasts were employed 1) treatment versus control, where each *time since cancer diagnosis* group compared against the *Healthy* and *Other Conditions* groups, and 2) pairwise comparisons within *Cancer* group, a) <1 year versus 1-5 years; b) <1 years versus >5 years; and c) 1-5 years versus >5 years.

To assess cancer types and 24-hour behaviour profile, a Bayesian multivariate model (b) was fitted with *ilr* coordinates representing 24-hour behaviour outcomes and *cancer type* predictor (16 categories of 14 cancer types and 2 non-cancer reference groups). Post-hoc contrasts, using the treatment versus control method, estimated the difference in the time spent in 24-hour behaviours

between each of the 14 cancer types and two control groups (*Healthy* and *Other Conditions*), respectively.

In line with previous studies[18 22 23], model (a) adjusted for age at accelerometry, sex, ethnicity, Townsend deprivation index, education/qualification attainment, employment, smoking status, and alcohol consumption, and season (see Supplementary Figure S1 for directed acyclic graph). Model (b) adjusted for the same covariates plus *time since cancer diagnosis* as this may vary by cancer type. All continuous covariates were modelled using smooth functions to account for possible non-linear associations. Models were fitted with weakly-informative priors and 4 chains with 2000 iterations (including 500 warmups per chain) for 6000 post-warmup draws. Model convergence was confirmed ($\hat{R} < 1.05$ and effective sample size > 400)[22]. The *ilr* coordinate estimates were back-transformed to minutes spent in 24-hour behaviours. Bayesian posterior means and 99% credible intervals were reported.

We then extracted the estimated 24-hour behaviour profiles by cancer type from model (b) and used a mixed-effects meta-regression model[24] to test the proportion of variance (R^2) across cancer types explained by their survival rate[24].

Finally, two additional analyses were performed. The first was an exploratory analysis on site-specific 24-hour behaviour profiles across time since diagnosis for cancer types with large sample sizes (>400 cases, including *Skin [non-melanoma], Prostate, Breast, Colorectal, Blood, Gynaecological*; see Supplementary Table S9 for a breakdown of cases by time since diagnosis and types), using a model with the *ilr* coordinates predicted by an interaction between time since cancer diagnosis categories and cancer types plus covariates. The second was a sensitivity analysis on 24-hour behaviours across time since cancer diagnosis excluding multiple cancers in model (a) as different cancer types may influence 24-hour behaviours in distinct ways.

Results

The analytical sample included 91 352 individuals [average age at accelerometer measurement (SD) = 62.3 (7.9) years; 56.4% female], details in Table 1. A participant flow diagram is in Supplementary Figure S2. There were 10 152 (11.1%, $M[SD]_{age}$ = 65.9 [6.8] years) participants in the *Cancer* group, 67 478 (73.9%, $M[SD]_{age}$ = 62.5 [7.7] years) in the *Other Conditions* group, and 13

722 (15.0%, $M[SD]_{age}$ = 58.7 [7.7] years) in the *Healthy* group. Individuals with *Cancer* had accelerometer measurements a mean of 7.4 (*SD* = 6.1) years after cancer diagnosis. The *Cancer* and *Other Conditions* groups had comparable numbers of other major chronic conditions by categories defined in the ICD-10, *M*(*SD*) = 2.6(1.8) vs. 2.6(1.5), respectively. Quantiles of 24-hour behaviour profile in individuals with cancer by demographic subgroups are in Supplementary Table S5.

24-hour profiles of individuals with and without cancer

Regardless of health status, participants allocated most of their day to SB, followed by sleep period, LPA, and lastly MVPA (Figure 1). Compared to *Healthy* individuals, individuals with *Cancer* spent less time in MVPA (-10.5 [99% CI -11.8, -9.3] min/day) and LPA (-14.4 [-17.9, -10.8] min/day) and more in SB (+10.9 [7.2, 14.9] min/day) and sleep period (+14.0 [11.3, 16.7] min/day). The estimated 24-hour behaviour profile of individuals with *Cancer* showed more similarity to that of individuals with *Other Conditions* than individuals who were classified as *Healthy*.

Differences in 24-hour behaviour profiles across time since cancer diagnosis

Throughout time since cancer diagnosis, individuals with Cancer showed significant differences in their 24-hour behaviours compared to Healthy individuals but are effectively comparable to those with Other Conditions (see Table 2 and Figure 1 for adjusted results and Supplementary Table S6 and Figure S3 for unadjusted results). The largest differences in 24-hour behaviour profiles were observed in individuals who were <1 year since cancer diagnosis. Compared to Healthy individuals, individuals with Cancer who were <1 year since diagnosis spent less time in MVPA (-11.8 [-14.4, -9.1] min/day) and LPA -28.4 [-36.6, -20.0] min/day) and more in SB (+20.0 [10.7, 29.7] min/day) and sleep period (+20.3 [13.6, 26.9] min/day). There were smaller differences for people who were 1-5 years since cancer diagnosis and >5 years since cancer diagnosis, compared to Healthy individuals.

Differences in 24-hour behaviours across cancer types

Individuals with different cancer types had different 24-hour behaviours compared to *Non-cancer* individuals, including those who are *Healthy* and those with *Other Conditions* (see Table 3 and Figure 2 for adjusted results and Supplementary Table S7 and Figure S4 for unadjusted results).

Among cancer types, individuals with *Gastrointestinal Tract* and *Lung* cancers showed the largest difference in their behaviours compared to *Non-cancer* individuals (Table 3 and Figure 2). Compared to *Healthy* individuals, individuals with *Gastrointestinal Tract* and *Lung* cancers spent less in MVPA (-20.9 [-25.8, -14.9] and -25.5 [-30.0, -19.7] min/day) and LPA (-53.3 [-77.1, -28.9] and -49.8 [-80.9, -16.7] min/day). They also had more SB (+53.4 [24.1, 82.8] and +41.7 [3.1, 78.7] min/day). Individuals with *Lung* cancer further had +33.6 [5.9, 61.5] longer sleep period. Similar patterns emerged compared to individuals with *Other Conditions,* but the magnitudes were smaller.

Meta-regression (Supplementary Table S8) showed that age-standardized, 5-year survival rates for different cancer types explained a substantial proportion of the variance in estimated MVPA (R^2 = 45.39%, p = .004), and SB (R^2 = 34.95%, p = .015), but not LPA (R^2 = 17.10%, p = .065) or sleep period (R^2 = 0%, p = .242).

Exploratory and sensitivity analyses

Exploratory analysis (Supplementary Figure S5) on 24-hour behaviours across type-specific time since cancer diagnosis analysis for six types of cancer with large sample sizes showed divergent patterns of 24-hour behaviours by time since cancer diagnosis. For example, the lowest MVPA level was found in individuals within <1 year since diagnosis for some but not all cancer types. Individuals with *Colorectal, Blood,* and *Gynaecological* cancers showed increased MVPA across time since diagnosis categories. Individuals with *Breast* and *Prostate* cancers both had lowest level of MVPA in the first year of diagnosis, with improvement in 1-5 years but not >5 years since diagnosis. Individuals with *Skin (non-melanoma)* had opposite trend, with decreased MVPA over time. Divergent patterns were also observed for other behaviours.

Sensitivity analysis (Supplementary Figure S6) on differences in 24-hour behaviour profiles across time since cancer diagnosis excluding *Multiple Primary* cancers showed materially consistent results to main analysis.

Discussion

In this large cohort study, we systematically described the 24-hour composition of physical activity, sedentary time, and sleep in individuals with cancer, benchmarked against non-cancer reference groups, considering time since cancer diagnosis and cancer type. We observed evidence of

24-hour behaviour alterations in individuals with cancer, with an overall profile of reduced physical activity across intensity levels and increased inactive time on a day-to-day basis. Compared to healthy individuals, individuals with cancer had less MVPA (↓ 11 min/day) and LPA (↓ 14 min/day), and more SB (↑ 11 min/day) and sleep period (↑ 14 min/day). Significant disruptions in 24-hour behaviours were observed in those within 1 year since diagnosis, and among cancers with low survival rates, including gastrointestinal tract and lung cancers.

24-hour behaviour profile across time since cancer diagnosis

Across the time since cancer diagnosis, the greatest deviation from the *Healthy* profile was observed in those within 1 year of cancer diagnosis, consistent with existing evidence[9 25 26]. Individuals in this category engaged in 40 min less physical activity (↓ 12 min/day in MVPA and ↓ 28 min/day in LPA) and instead allocated the time to inactive/resting behaviours (↑ 20 min/day in SB and ↑ 20 min/day in sleep period), compared to *Healthy* individuals. This amount of physical activity at the daily level can be substantial when accumulated over weeks and months (e.g., ≈84 min/week lower MVPA, ≈56% of the recommended 150 min/week MVPA). Notably, conservatively estimating the metabolic equivalents (METs) of LPA (1.5-3) and MVPA (≥3), the combined reduction of LPA and MVPA found in our participants with cancer is equivalent to 7 MET hours/week lower than healthy individuals, comparable to the 5.2-7.4 MET hours/week increase in the CHALLENGE exercise trial recently shown to improve disease-free survival[14]. Further, interventions targeting both physical activity and SB is effective for breast cancer survivors[27]. Our findings suggest increasing physical activity across intensities while simultaneously reducing SB is particularly needed in the first year after cancer diagnosis. Further, a holistic approach which considers time use across the whole day is warranted. A previous study highlighted the optimal 24-hour behaviour combination of moderate sleep duration and high MVPA was associated with lower mortality risk[28]. Future research may explore the optimal combination of 24-hour behaviours that are most favourably associated with disease-free and survival overall in individuals with cancer.

Our participants with cancer spent more time in sleep period than those without cancer; their average was 9.2 hours, exceeding the 7-9 hour threshold of optimal sleep recommended for healthy adults[29]. This may be due to our sleep period variable only capturing time in bed (time between sleep

onset and offset), rather than sleep duration (time actually sleeping). It is possible participants had a long sleep period but disrupted, unrestful sleep (e.g., longer sleep onset latency or night-time awakenings). Sleep difficulties persist well after diagnosis and completion of treatment[30 31] and throughout stages of cancer[32 33], thus requiring supportive care[34]. Further research should consider distinct sleep aspects, including objective sleep and wake time in bed, and subjective sleep complaints (e.g., difficulty initiating or maintaining sleep, and/or waking up too early). Objective and subjective sleep might both be useful to identify individuals for tailored sleep interventions, rather than universal "sleep more" recommendations. Individuals with extended time in bed with sleep problems may benefit from interventions focused on increasing sleep efficiency, by compressing sleep opportunity (time in bed) while maintaining sleep duration, such as cognitive behavioural therapy for insomnia[35 36]. Large clinical trials are required to confirm.

Individuals who were 1-5 years since cancer diagnosis had slightly more physical activity at the expense of inactive/resting time than those within 1 year since diagnosis, and individuals 5 years or more after cancer diagnosis showed even higher activity levels. The gradually favourable variations in 24-hour behaviours along the trajectory of survivorship may be due to cancer remission and side effect reduction after treatment[37]. Nevertheless, the 24-hour behaviour profile of individuals in the 5 years since cancer diagnosis category still significantly deviated from the healthy profile. This trajectory underscores the value of support for 24-hour behaviours spanning from diagnosis to long-term survivorship to meet the needs of the growing population of cancer survivors[3].

24-hour behaviour profile across cancer types

Across cancer types, physical activity regardless of intensity levels was lower than that in the *Non-cancer* group. High site-specific variability in time spent in 24-hour behaviours was observed, with some cancer types deviating significantly from the profile of healthy individuals, and some showing relative similarity. Age-adjusted 5-year survival rates by cancer type explained a large proportion of the variability (45% in MVPA and 35% in SB). Of the 14 cancer types examined, individuals with cancers that typically have low survival (e.g., lung [21% survival], gastrointestinal tract [22%]), were the least physically active, whereas those with high survival cancers (e.g., prostate [89%], melanoma [93%], skin) were more physically active. Lung and gastrointestinal tract cancers

with the worst prognoses (21% and 22%, respectively) had the least optimal 24-hour behaviour profiles; both having ~75 min/day less physical activity across intensity levels, alongside 53 and 42 min/day more SB, respectively, compared to healthy individuals. Further, our exploratory analysis on site-specific cancers showed divergent patterns of 24-hour behaviours by time since diagnosis. Although these results were based on smaller sample sizes, future research should consider that 24-hour behaviour composition trajectories may vary by cancer type. If replicated, these findings on pattern differences warrant mechanistic and conceptual studies to explain.

Although post-diagnosis physical activity was associated with improved survival across several cancer types[10], it is important to recognise that what is regarded as healthy might differ among individuals with cancer, especially those who are diagnosed with invasive cancer and undergo aggressive treatments. Among individuals with lung and gastrointestinal tract cancers, for example, trying to achieve a physical activity guideline threshold may be difficult. A more feasible approach could be maintaining physically active regardless of intensities while simultaneously reducing SB or optimising sleep. Further, intervention strategies tailored to their own specific needs and health goals, instead of emphasis on meeting general guidelines, may be necessary. For example, intervention targeting both physical activity and SB which is proven effective for breast cancer survivors [27] warrants evaluation in other cancer types. The large site-specific heterogeneity in sleep was not explained by estimated prognosis, highlighting the need to holistically explore distinct dimensions of sleep following diagnosis and treatment across cancer types to provide precise recommendations.

Strengths and limitations

The novelties of this study include the use of Bayesian compositional data analysis to model 24-hour behaviour composition as a multivariate outcome in a statistically valid way and obtain robust uncertainty estimates, while accommodating potential non-linear associations and adjustment for several plausible confounders. The large sample size enables comparison across time since cancer diagnosis and multiple cancer types. The wearables-based measures of behaviours overcome inherent limitations of self-report and provide useful evidence to enhance the current guidelines and interventions on 24-hour behaviours.

Despite being prospective, the observational design of the UKB only allows us to capture a snapshot of 24-hour behaviour profiles following cancer diagnosis. We cannot probe causality nor the within-person changes in 24-hour behaviour compositions from pre- to post-diagnosis. New methods for modelling longitudinal compositional data[20] highlight the feasibility of future research exploring the within-person, bidirectional relationship between cancer diagnosis and 24-hour behaviours. The potential misclassification of posture and movement, which is inherent to wearables, limits our ability to separate the effects of sleep duration versus time awake in bed, which is important for understanding sleep. Contextual determinants of 24-hour behaviours (e.g., occupational type, work schedule) were not explored, so physical activity may include both leisure and occupational activity. We combined vigorous versus moderate physical activities in our analysis, even though recent evidence suggests even small dose of vigorous physical activity was associated with reduced cancer risk[22].

This study is also limited by the lack of information on cancer stage, metastasis, and treatment in the UKB. Further, we did not exclude those with cancer alongside other conditions from the cancer group, given the high prevalence of multimorbidity (94%). Given cancer clinical complexity, it is difficult to precisely disentangle whether the other chronic conditions are contributors or consequences of cancer, and how they uniquely contribute to the 24-hour behaviour profile. Survival and selection biases from cancers with better prognoses and limited data on less common cancers may have skewed our observations toward a healthier profile. UK cancer survival rate is worse than other comparable countries[38], particularly for cancers with poor prognoses including lung and stomach[38], which may explain the low cases in our study. Results for cancer types with low cases (e.g., lung, endocrine gland, gastrointestinal tract) should be interpreted with caution and require future studies with more cases to confirm. Lastly, findings might not generalise, as the UKB is a predominately white and affluent population, with healthier participants than the UK general population[39 40]. Studies in nationally representative cohorts are necessary to evaluate the generalisability.

Conclusions

Public guidelines for healthy individuals have transitioned from providing guidance for independent behaviours and towards integrating 24-hour behaviours, but only general MVPA

recommendations are currently available for cancer survivors[8]. Our findings are supportive of an approach towards a healthy daily balance of physical activity, sedentary time, and sleep, rather than one-size-fits-all target of increasing physical activity for individuals with cancer. Reallocating 25 min/day to physical activity from inactive time may be incorporated in interventions and guidelines aimed at optimising 24-hour behaviours for cancer survivors. People with cancers that have poor prognoses, including lung and gastrointestinal tract cancers, and people within one year of cancer diagnosis had the least optimal 24-hour behaviour profiles, highlighting the need for further support and resources to be allocated to improve their survivorship care. Personalised intervention strategies may be necessary to support these subgroups of survivors in achieving and maintaining healthy 24-hour behaviour profiles, beyond standard guidelines for cancer survivors.

Ethics statement

The UK Biobank has generic ethical approval from the Northwest Multi-Centre Research Ethics Committee (11/NW/03820). Participants who accepted the invitation to join the UK Biobank cohort provided written, informed consent and were given reimbursement for travel expenses.

Disclosure statement

Financial Disclosure: ES is a paid consultant and holds equity in Complement 1, a US-based company whose products and services relate to physical activity and cancer risk reduction. All other authors declare no competing interests. Non-financial Disclosure: none.

Acknowledgement

We thank the participants in the UK Biobank and the UK Biobank for making the data and resources available.

Funding

This study is funded by Monash University, Australian Research Council (ARC) (DE230101174), National Health and Medical Research Council (NHMRC) (GNT1171981, APP1194510, 1178487), German Research Foundation (540707655), Wellcome Trust (223100/Z/21/Z, 227093/Z/23/Z), Novo Nordisk, Swiss Re, Boehringer Ingelheim, NIH Oxford-Cambridge Scholars Program, EPSRC Centre for Doctoral Training in Health Data Science (EP/S02428X/1), British Heart Foundation Centre of Research Excellence(RE/18/3/34214), Danish National Research Foundation (Pioneer Centre for SMARTbiomed), American Institute for Cancer Research (IIG849385), and American Heart Association (23CDA1050513).

Contribution statement

Guarantor: FL. Concept and design: FL and JFW. Acquisition, analysis, or interpretation of data: FL and JFW. Drafting of the manuscript: FL. Critical revision of the manuscript for important intellectual content: all authors. Obtained funding: DD. Administrative, technical or material support: FL and OD. Supervision: DD and JFW.

Data sharing statement

Data are available on application to the UK Biobank (www.ukbiobank.ac.uk/). This research is approved for access under application #62254. Analysis code for this study is available at

https://github.com/florale/ukb-cancer-24h. A preprint of this article is available at MedRxiv (https://doi.org/10.1101/2025.02.25.25322841). Preliminary findings from this study were presented at the 2025 National Cancer Survivorship Conference.

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Figure 1. Estimated 24-hour behaviour profile (in minutes per day) across time since cancer diagnosis.

Figure 2. Estimated 24-hour behaviour profile (in minutes per day) across cancer types.

Table 1. Participant characteristics (*N* = 91 352)

	Cancer *(n = 10 152)*	**Other Conditions** *(n = 67 478)*	**Healthy** *(n = 13 722)*
Age *M (SD)*	65.9 (6.8)	62.5 (7.7)	58.7 (7.7)
Sex *N (%)*			
Female	5 660 (55.8)	37 955 (56.2)	7 904 (57.6)
Male	4 492 (44.2)	29 523 (43.8)	5 818 (42.4)
White ethnicity *N (%)*	10 016 (98.7)	65 412 (96.9)	13 215 (96.3)
Body mass index *N (%)*			
Under to Normal weight (< 25 kg/m^2)	3 942 (38.9)	24 935 (37.0)	6 973 (50.9)
Overweight (25.0 to 29.9 kg/ m^2)	4 251 (42.0)	28 131 (41.8)	5 187 (37.8)
Obese (30+ kg/m2)	1 940 (19.1)	14 255 (21.2)	1 547 (11.3)
Education/qualification attainment *N (%)*	9 073 (89.4)	61 572 (91.2)	13 125 (95.6)
Employment *N (%)*	5 563 (54.8)	45 928 (68.1)	11 331 (82.6)
Townsend deprivation index *N (%)*			
Least deprived (< −3.8)	2 755 (27.1)	16 959 (25.1)	3 423 (24.9)
Second least deprived (−3.8 to −2.5)	2 557 (25.2)	16 010 (23.7)	3 239 (23.6)
Second most deprived (−2.5 to −0.2)	2 640 (26.0)	17 462 (25.9)	3 457 (25.2)
Most deprived (> −0.2)	2 200 (21.7)	17 047 (25.3)	3 603 (26.3)
Smoking *N (%)*			
Never	5 516 (54.3)	38 025 (56.4)	8 676 (63.2)
Previous	4 030 (39.7)	24 794 (36.7)	4 059 (29.6)
Current	606 (6.0)	4 659 (6.9)	987 (7.2)
Alcohol consumption *N (%)*			
Never	273 (2.7)	2 014 (3.0)	361 (2.6)
Previous	259 (2.6)	2 006 (3.0)	227 (1.7)
Current	9 620 (94.8)	63 458 (94.0)	13 134 (95.7)
Overall health rating *N (%)*			
Excellent	1 848 (18.3%)	12 895 (19.1%)	5 077 (37.0%)
Good	6 047 (59.8%)	40 892 (60.7%)	7 738 (56.4%)
Fair	1 875 (18.5%)	11 613 (17.2%)	850 (6.2%)
Poor	348 (3.4%)	1 952 (2.9%)	51 (0.4%)
Non-cancer conditions (by ICD chapters)			–
Any N (%)	9 456 (93.1%)		
M (SD)	2.56 (1.80)	2.58 (1.53)	
n (%)			
0	1 211 (11.93%)		
1	2 056 (20.25%)	19 887 (29.47%)	
2	2 141 (21.09%)	18 141 (26.88%)	
3	1 885 (18.57%)	13 141 (19.47%)	
4	1 348 (13.28%)	8 248 (12.22%)	
5+	1 511 (14.88%)	8 061 (11.95%)	
Time since cancer diagnosis *N (%)*		–	–
< 1 year	971 (9.6)		
1 to 5 years	3 451 (34.0)		
> 5 years	5 730 (56.4)		
Cancer type *N (%),* **median years since diagnosis**		–	–
Blood	412 (4.1), 7.4		
Breast	1 911 (18.8), 9.2		
Colorectal	391 (3.9), 6.5		
Endocrine Gland	79 (0.8), 9.5		
Gastrointestinal Tract	100 (1.0), 5.9		
Genitourinary	296 (2.9), 10.0		
Gynaecological	401 (3.9), 9.3		
Head and Neck	115 (1.1), 7.5		
Lung	57 (0.6), 5.5		
Melanoma	395 (3.9), 9.0		
Multiple Primary	1 714 (16.9), 6.4		
Other Cancer	148 (1.5), 10.7		
Skin (non-melanoma)	3 017 (29.7), 6.9		
Prostate	1 116 (11.0), 5.1		
Daily minutes in 24-hour behaviours *M (SD)*			
Moderate-to-vigorous physical activity	38.3 (32.8)	40.2 (34.3)	48.5 (36.5)
Light physical activity	296.7 (95.8)	302.8 (98.8)	308.3 (98.2)

Sedentary behaviour	566.4 (107.6)	565.6 (109.6)	557.0 (107.2)
Sleep period	538.7 (77.0)	531.5 (74.8)	526.2 (69.8)

Notes. Percentages may not sum to 100% due to rounding. Frequencies may not match columns precisely as missing data are excluded.

Table 2. Estimated minute per day differences in 24-hour behaviour profile across time since cancer diagnosis

	MVPA	LPA	SB	Sleep Period
ref. *Healthy*				
Cancer	**-10.5 [-11.8, -9.3]**	**-14.4 [-17.9, -10.8]**	**10.9 [7.2, 14.9]**	**14.0 [11.3, 16.7]**
<1 year since diagnosis	**-11.8 [-14.4, -9.1]**	**-28.4 [-36.6, -20.0]**	**20.0 [10.7, 29.7]**	**20.3 [13.6, 26.9]**
1-5 years since diagnosis	**-9.7 [-11.4, -8.0]**	**-18.0 [-22.8, -12.8]**	**12.3 [6.8, 17.9]**	**15.4 [11.5, 19.2]**
>5 years since diagnosis	**-10.8 [-12.3, -9.4]**	**-9.9 [-14.2, -5.5]**	**8.6 [4.0, 13.3]**	**12.1 [8.8, 15.4]**
ref. *Other Conditions*				
Cancer	**-1.3 [-2.2, -0.5]**	**-7.3 [-10.0, -4.5]**	**1.6 [-1.4, 4.8]**	**7.0 [4.7, 9.2]**
<1 year since diagnosis	-2.6 [-5.0, 0.1]	**-21.3 [-29.0, -13.2]**	**10.7 [1.9, 19.5]**	**13.2 [6.8, 19.7]**
1-5 years since diagnosis	-0.5 [-1.9, 1.0]	**-10.8 [-15.3, -6.2]**	3.0 [-2.1, 8.3]	**8.4 [4.8, 11.9]**
>5 years since diagnosis	**-1.6 [-2.7, -0.6]**	-2.7 [-6.3, 0.9]	-0.7 [-4.6, 3.3]	**5.1 [2.2, 7.9]**
Pairwise across time since diagnosis				
1-5 years since diagnosis ref. *<1 year since diagnosis*	2.1 [-0.9, 4.9]	**10.4 [1.2, 19.5]**	-7.7 [-17.9, 2.4]	-4.9 [-12.1, 2.2]
>5 years since diagnosis ref. *1-5 years since diagnosis*	-1.1 [-2.8, 0.5]	**8.1 [2.7, 13.7]**	-3.7 [-10.0, 2.4]	-3.3 [-7.5, 1.0]
>5 years since diagnosis ref. *<1 year since diagnosis*	1.0 [-1.8, 3.5]	**18.5 [10.2, 27.0]**	**-11.4 [-21.2, -2.1]**	**-8.1 [-14.8, -1.1]**

Values are Bayesian posterior mean differences and 99% credible intervals. Model adjusted for age at accelerometer, sex, ethnicity, Townsend deprivation index, education/qualification attainment, employment, smoking status, alcohol consumption, and season.
MVPA = moderate-to-vigorous physical activity, LPA = light physical activity, SB = sedentary behaviour. Bolded values indicate 99% credible intervals not containing 0.

Table 3. Estimated minute per day differences in 24-hour behaviour profile across cancer types. Values are Bayesian posterior mean differences and 99% credible intervals

	MVPA	LPA	SB	Sleep Period
ref. *Healthy*				
Prostate	-1.5 [-5.5, 2.5]	**-44.5 [-54.8, -34.8]**	**28.7 [16.9, 41.6]**	**17.3 [8.9, 26.2]**
Skin (non-melanoma)	**-7.4 [-10.1, -4.7]**	**-20.9 [-30.3, -12.9]**	9.0 [-0.3, 19.8]	**19.2 [12.3, 26.8]**
Melanoma	**-11.2 [-15.4, -6.7]**	**-17.5 [-33.1, -1.8]**	9.7 [-7.0, 27.3]	**19.0 [7.3, 30.7]**
Genitourinary	**-13.3 [-17.8, -8.5]**	**-43.4 [-59.3, -27.0]**	**37.7 [18.6, 57.3]**	**19.1 [5.7, 32.4]**
Other Cancer	**-13.5 [-19.3, -6.7]**	**-38.1 [-58.6, -16.5]**	**37.5 [12.5, 63.2]**	14.1 [-3.4, 32.0]
Colorectal	**-14.9 [-18.6, -10.9]**	**-15.9 [-30.7, -0.8]**	11.0 [-5.6, 28.1]	**19.8 [7.7, 32.4]**
Head and Neck	**-15.2 [-20.8, -8.1]**	-24.1 [-47.0, 1.4]	21.2 [-7.3, 48.9]	18.1 [-1.3, 38.4]
Endocrine Gland	**-15.4 [-22.0, -6.9]**	-8.9 [-38.4, 23.1]	11.6 [-21.1, 44.6]	12.7 [-11.1, 36.8]
Blood	**-16.5 [-19.8, -12.9]**	**-41.4 [-55.3, -27.7]**	**32.9 [16.8, 49.3]**	**25.0 [13.8, 36.4]**
Breast	**-18.1 [-20.5, -15.8]**	-4.1 [-15.0, 5.5]	4.0 [-6.7, 16.1]	**18.3 [10.3, 27.0]**
Gynaecological	**-19.7 [-22.8, -16.4]**	-8.7 [-23.6, 6.5]	13.3 [-2.8, 29.8]	**15.1 [3.7, 27.1]**
Gastrointestinal Tract	**-20.9 [-25.8, -14.9]**	**-53.3 [-77.1, -28.9]**	**53.4 [24.1, 82.8]**	20.9 [-0.6, 43.0]
Lung	**-25.5 [-30.0, -19.7]**	**-49.8 [-80.9, -16.7]**	**41.7 [3.1, 78.7]**	**33.6 [5.9, 61.5]**
Multiple Primary	**-13.1 [-15.7, -10.6]**	**-29.6 [-39.6, -20.4]**	**18.8 [8.4, 30.0]**	**23.9 [16.6, 32.1]**
ref. *Other Conditions*				
Prostate	**7.8 [3.9, 11.6]**	**-37.4 [-47.7, -28.0]**	**19.4 [8.1, 31.6]**	**10.2 [2.0, 18.7]**
Skin (non-melanoma)	1.9 [-0.6, 4.2]	**-13.8 [-23.1, -6.1]**	-0.2 [-9.4, 10.0]	**12.1 [5.2, 19.5]**
Melanoma	-1.9 [-6.0, 2.5]	-10.4 [-25.4, 5.2]	0.4 [-16.3, 17.9]	**11.9 [0.4, 23.5]**
Genitourinary	-4.1 [-8.2, 0.9]	**-36.3 [-52.1, -19.7]**	**28.4 [9.6, 47.8]**	12.0 [-1.4, 25.3]
Other Cancer	-4.3 [-10.0, 2.3]	**-30.9 [-51.2, -9.4]**	**28.2 [3.1, 54.2]**	7.0 [-10.5, 24.3]
Colorectal	**-5.6 [-9.1, -1.8]**	-8.8 [-23.9, 6.3]	1.8 [-15.0, 18.6]	**12.7 [0.9, 25.1]**
Head and Neck	-6.0 [-11.5, 1.1]	-16.9 [-39.6, 8.4]	11.9 [-16.4, 39.3]	11.0 [-8.4, 31.3]
Endocrine Gland	-6.2 [-12.7, 2.3]	-1.8 [-31.3, 30.0]	2.3 [-30.6, 35.1]	5.6 [-18.1, 29.7]
Blood	**-7.2 [-10.4, -3.8]**	**-34.3 [-47.8, -20.7]**	**23.6 [7.7, 40.0]**	**17.9 [6.5, 29.3]**
Breast	**-8.9 [-10.9, -6.9]**	3.0 [-7.7, 12.2]	-5.3 [-15.5, 6.6]	**11.2 [3.4, 19.5]**
Gynaecological	**-10.5 [-13.3, -7.3]**	-1.5 [-16.6, 13.1]	4.1 [-11.8, 20.0]	8.0 [-3.3, 19.9]
Gastrointestinal Tract	**-11.7 [-16.4, -5.6]**	**-46.2 [-69.6, -21.9]**	**44.1 [15.0, 74.1]**	13.8 [-8.1, 35.8]
Lung	**-16.3 [-20.6, -10.4]**	**-42.7 [-73.4, -9.1]**	32.5 [-6.1, 69.5]	26.5 [-1.4, 53.8]
Multiple Primary	**-3.9 [-6.1, -1.6]**	**-22.5 [-32.0, -13.7]**	9.6 [-0.6, 20.4]	**16.8 [9.7, 24.8]**

Model adjusted for age at accelerometer, sex, ethnicity, Townsend deprivation index, education/qualification attainment, employment, smoking status, alcohol consumption, season, and time since cancer diagnosis.

MVPA = moderate-to-vigorous physical activity, LPA = light physical activity, SB = sedentary behaviour. Bolded values indicate 99% credible intervals not containing 0.

Figure 1. Estimated 24-hour behaviour profile (in minutes per day) across time since cancer diagnosis. Values are Bayesian posterior mean differences and 99% credible intervals. Model adjusted for age at accelerometer, sex, ethnicity, Townsend deprivation index, education/qualification attainment, employment, smoking status, alcohol consumption, season. Vertical dashed lines represent estimated means, and shaded regions are 99% credible intervals of non-cancer groups (green = healthy, grey = other conditions). [a]significant difference from healthy, [b]significant difference from other conditions, [c]significant difference between <1y and 1-5y since diagnosis, [d]significant difference between 1-5y and >5y since diagnosis, [e]significant difference between <1y and >5y since diagnosis.

Figure 2. Estimated 24-hour behaviour profile (in minutes per day) across cancer types. Values are Bayesian posterior mean differences and 99% credible intervals. Model adjusted for age at accelerometer, sex, ethnicity, Townsend deprivation index, education/qualification attainment, employment, smoking status, alcohol consumption, season, and time since cancer diagnosis. Vertical dashed lines represent estimated means, and shaded regions are 99% credible intervals of non-cancer groups (green = healthy, grey = other conditions). [a]significant difference from healthy, [b]significant difference from other conditions.