Journal of Cystic Fibrosis xxx (xxxx) xxx

Contents lists available at ScienceDirect

Journal of Cystic Fibrosis

journal homepage: www.elsevier.com/locate/jcf

Original Article

Using heart rate data from wrist worn activity trackers to define thresholds for moderate to vigorous physical activity in children and young people with cystic fibrosis

Gizem Tanriver [a], Sanja Stanojevic [b], Nicole Filipow [a,b], Helen Douglas [a,c], Emma Raywood [a], Kunal Kapoor [a], Gwyneth Davies [d], Nicky Murray [e], Rachel O'Connor [f], Elisabeth Robinson [a], Eleanor Main [a,*]

[a] Physiotherapy, UCL Great Ormond Street Institute of Child Health, UCL, London United Kingdom
[b] Community Health and Epidemiology, Dalhousie University, Halifax, Nova Scotia, Canada
[c] Physiotherapy, Great Ormond Street Hospital for Children NHS Foundation Trust, London United Kingdom
[d] UCL Great Ormond Street Institute of Child Health, London United Kingdom
[e] Paediatric CF Unit, Royal Brompton Hospital, Guy's and St Thomas' NHS Foundation Trust, London United Kingdom
[f] Paediatric Cystic Fibrosis Centre, Royal London Hospital, Barts Health NHS Trust, London, United Kingdom

ARTICLE INFO

Keywords:
Children and young people
Cystic fibrosis
Moderate-to-vigorous physical activity
Activity tracker
Heart rate threshold
Linear mixed-effects model
Reference equation

ABSTRACT

Background: Children and young people with cystic fibrosis (CYPwCF) are encouraged to do an average of 60 min of moderate-to-vigorous physical activity (MVPA) daily. However, there are no agreed heart rate (HR) thresholds for defining MVPA, so it is difficult to ascertain whether these targets are actually achieved. Wearable activity trackers enable continuous monitoring of fitness-related measures such as HR and could be used to measure duration and intensity of habitual MVPA. We aimed to define personalized and responsive MVPA thresholds from HR in CYPwCF, to determine habitual time spent in MVPA during childhood and adolescence.

Methods: Continuous daily HR data were collected from 142 CYPwCF wearing activity trackers over 16 months. Linear mixed-effects models were used to develop personalised estimates of resting heart rate (RHR), peak heart rate (PHR) and MVPA thresholds, which were defined using the American College of Sports Medicine heart rate reserve (HRR) method.

Results: 309,926 days of physical activity data showed that both RHR and PHR declined with age in CYPwCF, with considerable variability within and between individuals. The HRR method produced personalised MVPA thresholds for each CYPwCF based on age, which inherently accounted for individual demographic variability and personal factors such as cardiovascular fitness or disease severity.

Conclusions: By accounting for within and between person variability in RHR and PHR, our novel method provides more accurate age-related personalised MVPA thresholds for CYPwCF than existing estimates. Our findings provide population-based estimates for RHR, PHR and MVPA thresholds at different ages in CYPwCF. This approach may help guide development of international standards for objective MVPA measurement in the era of remote HR and activity monitoring and facilitate accurate measurement of habitual physical activity in children and young people.

1. Introduction

The World Health Organization (WHO) recommends that children and young people (CYP) between the ages of 5 and 17 years achieve a daily average of 60 min of moderate-to-vigorous physical activity (MVPA) [1]. This recommendation includes those with chronic lung conditions such as cystic fibrosis (CF). However, there are no agreed standards on what heart rate (HR) threshold constitutes moderate physical activity, so it is difficult to ascertain whether daily MVPA targets have been achieved. Self-reported MVPA is not reliable in CYP [2–4], whereas wearable activity trackers, which enable continuous monitoring of fitness-related measures such as HR, have potential for

* Corresponding author at: UCL Great Ormond Street Institute of Child Health, University College London, 30 Guilford Street, London WC1N 1EH, United Kingdom.
E-mail address: e.main@ucl.ac.uk (E. Main).

https://doi.org/10.1016/j.jcf.2024.10.014
Received 11 April 2024; Received in revised form 3 October 2024; Accepted 31 October 2024

evaluating duration and intensity of daily MVPA to provide more objective estimates of habitual physical activity.

There remain a number of challenges to using HR data from wearable devices for quantifying MVPA in CYP, including those with chronic health conditions such as CF. Firstly, HR thresholds for defining MVPA in CYP remain unclear and conflicting in the literature [5–7] (Table 1, Fig. 1D). Published options variously define MVPA threshold as HR exceeding 120 bpm [5], or 70% of PHR [7] or 40% of HRR [8]. These are very different and all result in substantially different assessments of daily MVPA in individuals. Efforts to benchmark habitual activity against WHO recommendations are not possible because of this lack of standardisation.

Secondly, age dependent algorithms for defining MVPA threshold in adults (Table 1), have been derived from adult HR data only and are not appropriate for CYP, as normal HR ranges in childhood differ from adults (note adult MVPA threshold equations in Fig. 1D for context). In addition, both RHR and PHR decline with age during childhood, so fixed MVPA thresholds such as that offered by Riddoch [5,6] risk age bias in estimating MVPA.

Finally, age dependent MVPA algorithms and fixed thresholds do not account for differences in cardiovascular fitness or clinical circumstances. This means that all CYP of the same age are assumed to be exercising 'moderately' if their HR is ~125bpm. In reality, a deconditioned 8-year-old child with significant lung disease (RHR: 90) may experience a 3-minute step test as an extremely vigorous activity, with HR responses to match, while a fit healthy 8-year-old (RHR: 70) may not find it very tiring at all. Therefore, any estimation of 'time in MVPA' per day from HR must account for individual differences in age, fitness, clinical circumstances and other factors that affect the experience of physical exertion. In other words, MVPA thresholds should be both personalised and responsive to age and physical changes over time.

The American College of Sports Medicine (ACSM) offers personalised calculation of MVPA thresholds in adults as a percentage of the difference between Resting Heart Rate (RHR) and Peak Heart Rate (PHR), called the Heart Rate Reserve (HRR) method. This provides the potential to provide more accurate personalised estimates of MVPA, since it does not rely on age alone [8]. Both RHR and PHR change as a function of age as well as fitness and clinical circumstances, so these equations would inherently 'express' the body's physiological adaptations to age, illness or training within the MVPA threshold that is derived from them. The HRR is therefore likely to be the most appropriate approach for evaluating habitual physical activity or exercise over time in populations of CYP with long term clinical conditions, where all these factors come into play and influence physical activity to a greater or lesser extent [9,10,12].

Obtaining regular or continuous measurements of RHR and PHR in CYP is not trivial, and normative datasets do not currently exist. In particular, RHR data are not freely available in CYP, partly because any measures taken in clinical or research settings are likely to result in anxiety and elevated RHR readings, adding to the challenge of using the HRR method for defining MVPA in CYP.

This study aimed to utilise real-world longitudinal HR data from CYPwCF who: a) wore a Fitbit activity tracker regularly over a 16month period and b) had PHR data from a 25-level 10-metre modified shuttle walk/run test (10mMST-25) at the beginning of the study to:

1. Calculate individualised MVPA thresholds in CYPwCF, using the ACSM HRR method
2. Define population-based estimates of RHR, PHR and MVPA thresholds at different ages, so that these might be used as a benchmark by others in the absence of continuous HR data
3. Describe a method for determining habitual time spent in MVPA during childhood and adolescence from HR data, to improve rigour and standardisation in future

Table 1
Summary of commonly used methods for calculating MVPA threshold.

Author, Year	Population	PHR Calculation	MVPA Threshold Calculation
Fox et al., 1971 [9]	Adults	(220 - Age)	HR > (220 - Age) x 0.5 *
Tanaka et al., 2001 [10]	Adults (Healthy)	(208 - (0.7 x Age))	HR > (208 - (0.7 x Age)) x 0.5 *
ACSM, 2014 [8]	Adults	–	PHR Method: HR > PHR x 0.64 HRR Method: HR > (PHR - RHR) x 0.4 + RHR
Riddoch and Boreham, 1995 [5, 6]	Children	–	HR > 120 bpm
Swisher et al., 2015 [7]	Adults and Children	–	HR > PHR x 0.7

* The calculations are based on the HR zones proposed by the Centers for Disease Control and Prevention (CDC). An adult's HR should be at least 50% of their age-related PHR to be considered MVPA [11]. PHR= Peak heart rate; MVPA=Moderate to vigorous physical activity; HR=Heart rate; ACSM=The American College of Sports Medicine, RHR= Resting heart rate.

2. Methods

2.1. Study population

Project Fizzyo was a longitudinal observational paediatric cohort study, conducted in the United Kingdom. Recruited participants were: (1) aged 6–16 years, (2) diagnosed with CF and (3) under the care of a participating London paediatric CF centre (Great Ormond Street Hospital (GOSH), the Royal London Hospital (RLH) or the Royal Brompton Hospital (RBH)). Participants were asked to wear a Fitbit Alta HR activity tracker (San Francisco, USA) over a period of 16 months [13]. Children < 6 years were not recruited because they could not reliably undertake the 10mMST-25 exercise test, and the Fitbit Alta did not have wrist straps compatible with very small wrist sizes. Because of the extended study period, there was concern that older participants might transition to an adult CF care centre during the study, so the oldest recruits were 16 years of age (during the 16-month study period they also contributed RHR data as 17-year-olds).

Project Fizzyo aimed to evaluate patterns and impact of daily habitual physical activity via remote monitoring. The study was approved by the London-Brighton and Sussex NHS Research Ethics Committee (18/LO/1038, IRAS: 228,625). Participants were recruited between September 2018 and July 2019. Participants and/or their guardians provided informed consent.

2.2. Data processing

To evaluate patterns of physical activity, raw HR values were extracted from Fitbit and a data processing pipeline was developed in R for cleaning and featurising data. Fitbit sampling frequency varied between 6 and 30 times per minute based on intensity of physical activity; therefore, raw HR values were averaged per minute every day. A daily RHR was calculated per participant as the average of the 5 lowest HR values (mean HR per minute) during waking hours [14,15]. The time window was restricted to waking hours as low HR during sleep can cause underestimation of RHR and therefore the MVPA threshold. There is a clear circadian rhythm in HR, and while true RHR occurs during sleep, definitions of RHR used for equations such as the ACSM HRR method for calculating MVPA usually refer to individuals being awake but at rest and inactive.

All participants completed a 25-level 10-metre modified shuttle walk/run test (10mMST-25) as a test of maximal exercise capacity at recruitment [16,17]. It is an easily accessible, standardised, low cost, reliable and validated field test, requiring no specialist equipment or

staffing. It has the potential to extract a near maximal physical effort from participants and can produce reliable PHR values. In addition, 78 participants completed a second 10mMST-25 between 7 and 9 months later. The study period coincided with the Covid-19 pandemic which precluded a second test in around half of the participants. No CYPwCF were able to complete all 25 levels of the 10mMST-25.

Participants wore their Fitbit and a chest-worn Polar H10 single-lead ECG monitor during each 10mMST-25. Consistent with previous studies, Fitbit data tended to underestimate HR during strenuous activity in comparison to the HR values recorded by ECG devices [18–21], therefore PHR data from the Polar HR monitor during all 10mMST-25 were used in the analyses. Only PHR measurements indicating a valid near-maximal effort (PHR>180 bpm) in the 10mMST-25 field exercise test were included to ensure acceptable levels of effort from participants. This resulted in exclusion of 22 of the 220 PHR measurements from the analysis (10%).

Linear mixed effects regression (LMER) models, which account for repeated measures within participants, were used to derive the equations for PHR and RHR using the lme4 package in R 3.6 [22]. Participant age was modelled as a fixed effect, ID and age were modelled as random effects (random intercept and slope). The final model was selected based on the smallest Akaike Information Criteria (AIC) and Bayesian Information Criteria (BIC).

The personalised daily MVPA threshold for each CYPwCF was calculated using the ACSM HRR method [8] based on daily personalised RHR and PHR calculated from the derived equations for each participant in the study. The calculated MVPA threshold values were rounded to the nearest integer. For days where a threshold could not be estimated, measured data from the closest day available was used.

3. Results

3.1. Participants

There were 145 CYPwCF recruited to the study aged 6.0–16.7years (mean 10.2years), with comparable numbers of males and females (Table 2). Mean FEV_1 was 88.3% predicted at baseline. Eight CYPwCF were prescribed CFTR modulators at enrolment and an additional 24 commenced modulators during the study. After exclusions (3 participants did not sync any Fitbit data after enrolling), 142 participants contributed physical activity data over a median (IQR) period of 178 (69–338)days. No participants wore their Fitbit for every day during the study, so there were days with missing RHR data. All available data from the 142 participants were used in the analyses regardless of length of time in the study. The LMER regression analysis per participant allowed for RHR to be estimated on days when participants did not wear their Fitbit.

Table 2
Summary of demographic variables in the study population of children and young people with CF. Mean (SD) [Range] unless otherwise stated.

	Units	Fizzyo Participants
Participants	n	145
Age at Recruitment	years	10·2 (2·8) [6.0 – 16·7]
Females	n (%)	71 (49)
Males	n (%)	74 (51)
BMI	kg/m^2	17.4 (2.7) [13.1 – 30.5]
BMI	z-score	0.1 (1.0) [−2.1 – 2.7]
10mMST-25 Distance	metres	994 (228.8) [390 – 1540]
10mMST-25 PHR	bpm	197 (8.7) [180 – 218]
RPE (OMNI) after 10mMST-25	-	8.3 (1.7) [2.0 – 10.0]
F508del	Heterozygous n (%)	79 (54)
	Homozygous n (%)	46 (32)
	No Copies n (%)	20 (14)
FEV_1	% predicted	88·3 (15·2) [36·8 – 121·6]
FVC	% predicted	95·4 (13·4) [44·4 – 126·3]
CFTR modulators	Baseline n (%)	8 (6)

BMI= Body mass index; 10mMST-25 = 25-level,10-metre Modified Shuttle Test; PHR= Peak heart rate; RPE (OMNI) = Rate of Perceived Exertion, using the OMNI Picture System, a collection of picture category scales used to rate exertion; F508del= F508del is the most common mutation in CF; FEV_1= forced expiratory volume in 1 second; FVC: forced vital capacity; CFTR=cystic fibrosis transmembrane conductance regulator.

3.2. Resting heart rate

A total of 309,926 days of physical activity data from 142 participants were available. Daily RHR varied within and between participants (Fig. 1A). The average RHR at age 6 was 79 bpm, 95% CI [76, 82] and this decreased with age (slope = −0.99, 95% CI [−1.61, −0.36], p = 0.002) (Fig. 1B). Within repeated measures in the same participant, the day-to-day variability of RHR was only 7.99 bpm, whereas between individuals RHR varied by 33.14 bpm.

LMER Equation 1: $RHR_{ij} = 85.41 - 0.99\ age_{ij} + u_{0i} + u_{1i}\ age_{ij} + \varepsilon_{ij}$ (Figs. 1A and B) where i is the participant ID and j is a given timepoint. u_0 and u_1 are the random intercept and slope coefficients respectively for participant i, and ε_{ij} is the residual error for participant i at timepoint j.

3.3. Peak heart rate

The average PHR at age 6 was 199 bpm (95% CI [196, 201]) and this decreased with increasing age (slope = −0.51, 95% CI [−0.98, −0.03], p-value=0.038), (Fig. 1C). The variability of Peak Heart Rate between participants was 7.1 beats per minute.

LMER Equation 2: $PHR_i = 201.89 - 0.51\ age_i + u_{0i} + \varepsilon_i$ (Fig. 1C) where i is the participant ID, u_0 is the random intercept and ε_i is the residual error for participant i.

3.4. MVPA threshold

Using the derived RHR and PHR equations, the within-subject MVPA thresholds were calculated (Fig. 1D).

LMER Equation 3: $MVPA\ Threshold_{ij} = RHR_{ij} + 0.4 * (PHR_i - RHR_{ij})$ (Fig. 1D) where i is the participant ID and j is a given timepoint, and RHR and PHR are derived from Equations 1 and 2 above. On average, the MVPA threshold decreased by 0.68 bpm per year of age (SD=1.65, 95% CI [−0.95, −0.40])

These data confirm that both RHR and PHR slowly decline over time with age in CYP (black lines in Figs. 1A, B, C), but with different slopes. Both RHR and PHR are therefore important to include in calculating MVPA thresholds for CYPwCF, and the HRR method appropriately accommodates for changes with age.

These data also very clearly indicate that despite the overall average decline in RHR with age in CYP, some individual RHR slopes increased over time during the course of their participation in the study, or decreased more or less than could be explained by age alone (Fig. 1B). These changes in RHR over time, which do not follow the trend of anticipated decline due to age alone, likely reflect other personal factors that may include change in cardiovascular fitness, declining or improving health, or other physiological factors that impact RHR.

Based on this large dataset, the average predicted values for RHR, PHR and MVPA threshold for CYP vary by age (Table 3). In the absence of individual daily RHR and/or PHR data, the derived equations and values in Table 3 can be used as reasonable estimates for prescribing HR thresholds for MVPA. However, with sufficient repeated measures in a participant during clinical stability, an individual's own data can be used to generate an MVPA threshold. Given the wide variance observed between-participants, individualised thresholds would provide the most accurate estimate of an individual's MVPA threshold.

4. Discussion and conclusion

We propose a method for personalised estimates of MVPA thresholds in CYP which accounts for within and between participant variation in

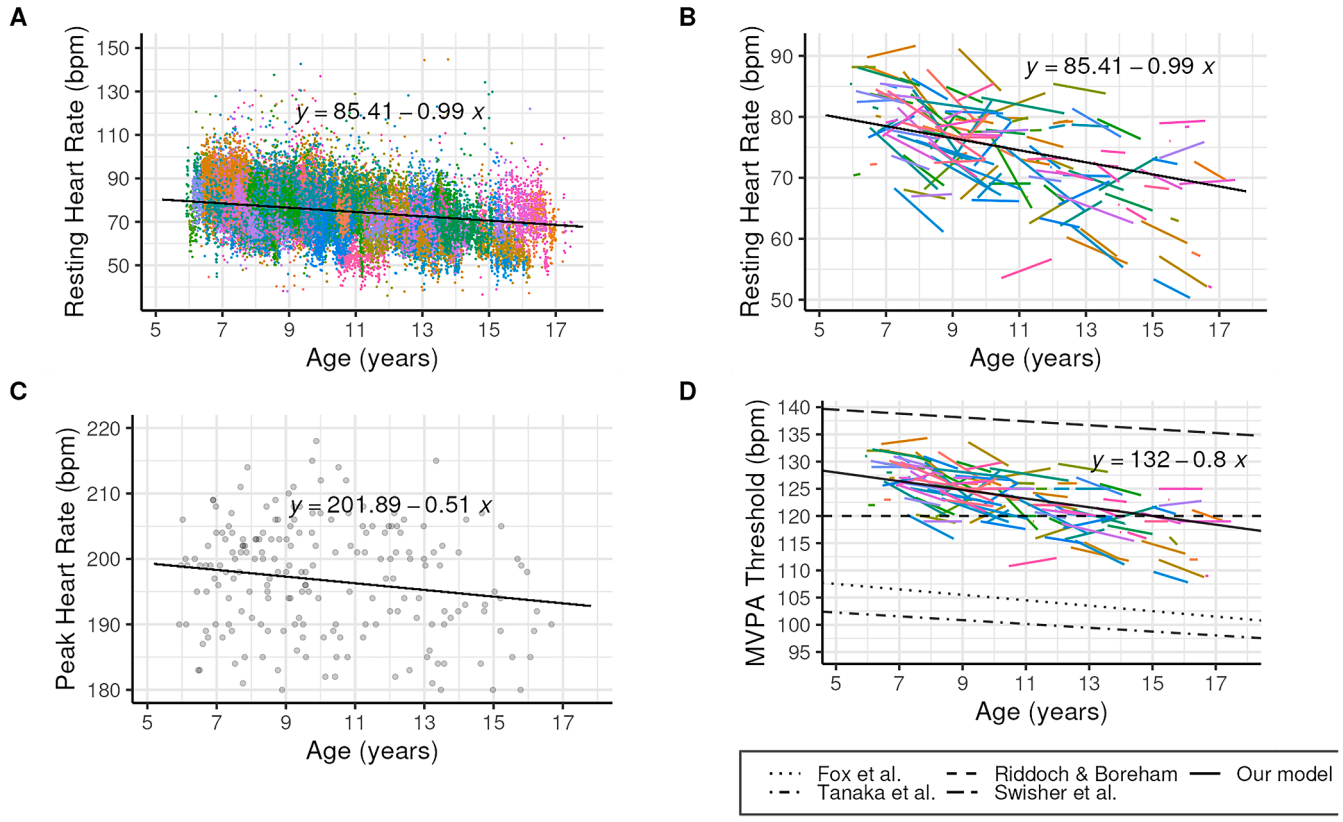

Fig. 1. A) Daily Resting Heart Rate (RHR) in beats per minute (bpm) per participant. B) Personalised slopes predicted by the LMER model derived daily RHR in bpm for each participant. C) Age-dependent Peak Heart Rate (PHR) for each participant in bpm. D) Personalised MVPA threshold in bpm, calculated for each participant in the study using the personalised LMER RHR and PHR equations. Overlaid for context are the adult MVPA threshold regression equations from Table 1 [9,10], and the paediatric thresholds suggested by Swisher et al. [7] and Riddoch and Boreham [6].

Table 3
Average RHR, PHR and MVPA threshold for different ages in CYPwCF.

Age (years)	*RHR (bpm)*	*PHR (bpm)*	*MVPA threshold (bpm)*
6	79.5	198.8	127.2
7	78.5	198.3	126.4
8	77.5	197.8	125.6
9	76.5	197.3	124.8
10	75.5	196.8	124.0
11	74.5	196.3	123.2
12	73.5	195.8	122.4
13	72.5	195.3	121.6
14	71.6	194.8	120.8
15	70.6	194.2	120.0
16	69.6	193.7	119.2
17	68.6	193.2	118.4

RHR and PHR, and thus accounts for inter-individual differences in factors such as cardiovascular fitness or demographic variability. Inherently, personalised equations also account for factors arising from presence or severity of disease in individuals. These thresholds can be applied to practical objective evaluation of habitual MVPA against targets or prescriptions.

Our data showed that within the same participant RHR varied by around 8 bpm from day-to-day. It would not make sense to adjust personal MVPA threshold on the basis of potentially spurious daily fluctuations in RHR. The personalised LMER equations for RHR therefore provided an important smoothing function, removing 'noise' in daily RHR measures, but retaining responsiveness to sustained changes over time, likely due to age, fitness or clinical circumstances. It also allowed for RHR to be estimated on days when participants did not wear their Fitbit. These personal variations over time confirmed a) how important it is to set personalised MVPA thresholds that are responsive to the complexity of factors influencing RHR and PHR over time and b) that the ACSM HRR method incorporated into these population based LMER equations reflect important personal circumstances that appropriately contribute to the setting of individual MVPA thresholds. These personalised and responsive MVPA thresholds are feasible to use and provide a robust and repeatable method for estimating time in MVPA and changes in habitual physical activity over time relative to the physiological exercise capacity of the individual at the time.

Daily use of activity trackers which record HR, such as Fitbit devices, can help capture objective measures of MVPA in CYP. While activity trackers may not provide HR data with quite the same accuracy as clinical ECG devices, photoplethysmography sensors produce excellent HR measurement, with an absolute error approximating 5% in real world settings [23]. This is more than acceptable given the advantages of these sensors, including scalability and low participant burden [24]. Participants are much more likely to wear them over extended periods, facilitating more accurate longitudinal evaluation of habitual physical activity compared with self-report. Importantly, taking into account the within-person variability of both RHR and PHR allows for more appropriate thresholds of MVPA to be established. Commercial activity tracker devices often use proprietary, 'black box' algorithms to interpret HR data, which are largely based on adult data, and are not appropriate for estimating MVPA in CYP. These data confirm that published adult thresholds for MVPA substantially overestimate MVPA in CYP [9,10] (Fig. 1D), while the 120 bpm Riddoch and Boreham [6] threshold overestimates MVPA in younger children and underestimates MVPA in adolescents. The Swisher threshold [7] appears substantially higher than all others assessed.

Use of activity trackers also allows for repeated measures of RHR at the individual level and therefore calculation of accurate personalised

MVPA threshold. Clinical, epidemiological or research groups using their own HR data in CYP, may use the proposed LMER Equations 1,2,3 above, which account for age-related changes in RHR and PHR and facilitate more accurate estimates of MVPA than the single 120 bpm threshold suggested for CYP by Riddoch and Boreham in 1995 [5,6] or self-report. If continuous measures of RHR and/or PHR are not available, the simple linear equations in Fig. 1 for RHR, PHR, or MVPA population average data may also be used as a reasonable threshold estimation for calculating physical activity in CYP. The RHR and PHR equations (Fig. 1, B and C) can also be used to facilitate calculations of other bespoke MVPA thresholds as a function of either PHR (eg 50, 60, 70% of PHR), or HRR methods (eg 50, 60, 70% of HRR). The novel methods described may go some way to address the longstanding challenge of predicted maximal heart rate in children, which were summarised in a systematic review and meta-analysis by Cicone et al. [19].

Our novel approach to define personalised estimates of RHR, PHR and MVPA thresholds uses data from participants with CF. We acknowledge this dataset may not be representative of a general population of CYP in terms of MVPA or RHR, although our cohort's high mean FEV_1 (~88% predicted) indicates a relatively healthy population of CYPwCF and Fig. 1D suggests that our data may approximate the Riddoch and Boreham 120 bpm MVPA threshold for a healthy general population of CYP [6].

The equations generated by this, albeit large dataset, do not purport to be a definitive MVPA threshold for all CYP. Instead, our data from a disease-specific study population demonstrates the methodology and rationale for this approach. The equations offer more accurate age related MVPA thresholds for CYPwCF than currently exist in the literature, and a route to developing an international standard for MVPA measurement in the era of remote activity monitoring and big data. Future research can extend the application and evaluation of this approach in healthy populations, as well as other disease or condition-specific populations.

Conflict of interest statement

GD reports speaker honoraria from Chiesi Limited, and speaker honoraria, advisory board and clinical trial leadership roles from Vertex Pharmaceuticals unrelated to the current study. SS reports consulting fees from Cheisi and ndd, and speaker fees from Vyaire medical unrelated to the current study. None of the authors have any financial or personal relationships with other people or organisations that inappropriately influenced this work.

CRediT author statement

Tanriver, Gizem; Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing – original draft, review & editing, Visualization, Stanojevic, Sanja; Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing – original draft, review & editing, Supervision, Filipow, Nicole; Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing – original draft, review & editing, Visualization, Douglas, Helen; Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, review & editing, Funding acquisition, Raywood, Emma; Methodology, Validation, Investigation, Writing- review & editing, Visualization, Project administration, Kapoor, Kunal; Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Davies, Gwyneth; Writing- review & editing, Murray, Nicky; Investigation, Writing- review & editing, O'Connor, Rachel; Investigation, Writing- review & editing, Robinson, Elisabeth; Writing - review & editing, Main, Eleanor; Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, review & editing, Visualization, Supervision, Project administration, Funding acquisition

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank the paediatric CF teams at the Great Ormond Street, Royal Brompton and Royal London Hospitals. We also thank the GOSH Digital Research Environment (DRE) team, especially Neil J. Sebire and John Booth. This research was made possible with the support of Tim Kuzhagaliyev and Microsoft UK, especially Greg Saul, Lee Stott and the Microsoft CSE team (including Olga Liakhovich, Tempest Van Schaik, Bianca Furtuna, Josh Lane, Pete Roden, Stephanie Marker, Christian Robles, Kristjana Popovski, Hannah Kennedy and Kristin Ottofy) who helped develop the data cleaning and processing pipeline.

This work was supported by the UCL Rosetrees Stoneygate prize (M712), a Cystic Fibrosis Trust Clinical Excellence and Innovation Award (CEA010), and a UCL Partners award (EM, GT, ER, KK). HD was funded by the CF Trust Youth Activity Unlimited SRC and an NIHR GOSH BRC internship. NF received funding from a UCL, GOSH and Toronto SickKids studentship. GD is supported by a Future Leaders Fellowship from UK Research and Innovation (MR/T041285/1). All research at Great Ormond Street Hospital NHS Foundation Trust and UCL Great Ormond Street Institute of Child Health is made possible by the NIHR Great Ormond Street Hospital Biomedical Research Centre. The views expressed are those of the authors and not necessarily those of the NHS, the NIHR or the Department of Health and Social Care. The study was sponsored by UCL. The funders and sponsor played no role in the design of the study.

References

[1] World Health Organization, "Physical activity," 26-Nov- 2020. [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/physical-activity. [Accessed: 18-Aug-2021].
[2] LeBlanc AGW, Janssen I. Difference between self-reported and accelerometer measured moderate-to-vigorous physical activity in youth. Pediatr Exerc Sci 2010; 22(4):523–34.
[3] A. Downs, J. Van Hoomissen, A. Lafrenz, and D.L. Julka, "Accelerometer-Measured Versus Self-reported Physical Activity in College Students: Implications for Research and Practice," 2014.
[4] Sallis JF. Self-report measures of children's physical activity. J Sch Health 1991;61 (5):215–9.
[5] Rowlands AV, Eston RG. The Measurement and Interpretation of Children's Physical Activity. J Sports Sci Med Sep. 2007;6(3):270.
[6] Riddoch CJ, Boreham CAG. The Health-Related Physical Activity of Children. Sport. Med. Oct. 1995;19(2):86–102.
[7] Swisher AK, et al. Exercise and Habitual Physical Activity for People With Cystic Fibrosis. Cardiopulm Phys Ther J Dec. 2015;26(4):85–98.
[8] Lippincott Williams & Wilkins. ACSM's guidelines for exercise testing and prescription. 9th ed. American College of Sports Medicine; 2014.
[9] Fox S, Naughton J, Haskell W. Physical activity and the prevention of coronary heart disease. Ann Clin Res Dec. 1971;3(6):404–32.
[10] Tanaka H, Monahan KD, Seals DR. Age-predicted maximal heart rate revisited. J Am Coll Cardiol Jan. 2001;37(1):153–6.
[11] Centers for Disease Control and Prevention. Target Heart Rate and Estimated Maximum Heart Rate. Physical activity. CDC; 2018. 12-Nov-[Online]. Available: https://web.archive.org/web/20181112171920/https://www.cdc.gov/physicalactivity/basics/measuring/heartrate.htm [Accessed: 13-Dec-2021].
[12] Y. Ostchega, K.S. Porter, J. Hughes, M.P. H. ; Charles, F. Dillon, and T. Nwankwo, "Resting Pulse Rate Reference Data for Children, Adolescents, and Adults: United States, 1999-2008," 1999.
[13] Raywood E, et al. Protocol for Project Fizzyo, an analytic longitudinal observational cohort study of physiotherapy for children and young people with cystic fibrosis, with interrupted time-series design. BMJ Open Oct. 2020;10(10). p. e039587.
[14] Logan N, Reilly JJ, Grant S, Paton JY. Resting heart rate definition and its effect on apparent levels of physical activity in young children. Med Sci Sports Exerc 2000; 32(1):162–6.
[15] Kapoor K, et al. Determining resting heart rate in children using wearable activity monitors. Eur Respir J Sep. 2019;54(suppl 63):PA342.

[16] Corda J, Holland AE, Berry CD, Westrupp N, Cox NS. Validation of the 25 level modified shuttle test in children with cystic fibrosis. Pediatr Pulmonol Aug 2023;58 (8):2240–8.
[17] Elkins MR, Dentice RL, Bye PT. Validation of the MST-25: an extension of the modified shuttle test (MST). J Cystic Fibr 2009;8:S70.
[18] Kroll RR, Boyd JG, Maslove DM. Accuracy of a wrist-Worn wearable device for monitoring heart rates in hospital inpatients:A prospective observational study. J. Med. Internet Res. Sep. 2016;18(9):e6025.
[19] Wang R, et al. Accuracy of wrist-worn heart rate monitors. JAMA Cardiol Jan. 2017;2(1):104–6.
[20] Cadmus-Bertram L, Gangnon R, Wirkus EJ, Thraen-Borowski KM, Gorzelitz-Liebhauser J. The accuracy of heart rate monitoring by some wrist-worn activity trackers. Ann Intern Med 2017;166(8):610–2. NIH Public Access18-Apr-.
[21] Benedetto S, Caldato C, Bazzan E, Greenwood DC, Pensabene V, Actis P. Assessment of the fitbit charge 2 for monitoring heart rate. PLoS One Feb. 2018;13 (2):e0192691.
[22] Bates D, Mächler M, Bolker BM, Walker SC. Fitting Linear Mixed-Effects Models Using lme4. J Stat Softw Oct. 2015;67(1):1–48.
[23] Nelson BW, Allen NB. Accuracy of Consumer Wearable Heart Rate Measurement During an Ecologically Valid 24-Hour Period: Intraindividual Validation Study. JMIR mHealth uHealth Mar. 2019;7(3):e10828.
[24] Chevance G, et al. Accuracy and Precision of Energy Expenditure, Heart Rate, and Steps Measured by Combined-Sensing Fitbits Against Reference Measures: Systematic Review and Meta-analysis. JMIR mHealth uHealth Apr. 2022;10(4).