Original Research

Implementing Wearable Sensors for Continuous Assessment of Daytime Heart Rate Response in Inpatient Rehabilitation

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Abstract

Background: *It is unclear whether wearable heart rate (HR) sensors can be worn continuously in inpatient rehabilitation to assess cardiorespiratory training response. If feasible, these sensors offer a low-cost low-maintenance method for assessing HR response in this setting. We determined feasibility of wearable sensors for assessing HR response to daytime therapy activities in inpatient rehabilitation within a cardiorespiratory training zone equal to 55–80% of maximal HR (target HR [THR]) for at least two 10-min bouts, 3–5 days per week. Secondarily, we determined episodes of excessive HR (EHR >80% of maximal HR).*

Materials and Methods: *Subjects 44–80 years of age with diagnoses of stroke, cardiac disorders, orthopedic disorders, medically complex conditions, or pulmonary disorders wore wrist-mounted HR sensors day and night throughout inpatient rehabilitation. The proportion of subjects meeting THR thresholds and experiencing EHR episodes was quantified. Multiple regression predicted THR and EHR outcomes from age, sex, length of stay, and motor function at admission and discharge.*

Results: *Across subjects, 97,800 min of HR data were analyzed. Sixty percent of subjects met THR thresholds for cardiorespiratory benefit. Age was the single significant predictor of percent of days meeting the THR threshold ($R = 0.58$, $p = 0.024$). Forty-seven percent of subjects experienced EHR episodes on at least 1 day. No subjects experienced sensor-related adverse events, and no protocol deviations occurred from inadvertent sensor removal.*

Conclusions: *Most subjects experienced HR increases sufficient to obtain cardiorespiratory benefit. Likewise, most subjects had episodes of EHR. Wearable sensors were feasible for continuously assessing HR response, suggesting expanded opportunity in inpatient rehabilitation research and treatment.*

Keywords: *telemedicine, telehealth, rehabilitation, technology, cardiology, sensor technology*

Introduction

Physical activity in inpatient rehabilitation is used to improve physical function after a debilitating medical event. Wearable activity monitors hold promise as a tool to assist clinicians in this setting to understand whether physical activity is of sufficient intensity to improve physical function. While activity monitors commonly characterize the activity level in terms of step count, evidence suggests that these devices inaccurately count steps in individuals who walk very slowly and/or have gait impairment. Diminished accuracy in detecting when a step has occurred in slow or impaired gait has been shown in various populations, from community-dwelling elderly[1] to inpatient rehabilitation patients.[2–4] Despite decreased accuracy with decreased walking speed, specific commercially available monitors have utility in an inpatient rehabilitation setting for monitoring other aspects of exercise intensity, such as the heart rate (HR) during therapeutic activity. HR monitoring has an advantage over counting steps, in that it is a more direct measure of intensity of activity; has immediate value to make clinical decisions, as opposed to waiting for the accumulation of steps across a day; has value for assessing intensity of effort for activities other than walking; and is not affected by the use of walking aids, such as walkers or canes. No studies to date have examined the feasibility of long-term assessment of HR in inpatient rehabilitation.

Evidence is clear and consistent that individuals receiving inpatient rehabilitation services can improve cardiorespiratory function from participation in a structured, prescriptive, aerobic activity program that reaches intensity, duration, and frequency thresholds to stimulate an aerobic training benefit.[5–7] Yet, previous studies have reported that the intensity of physical activity during inpatient rehabilitation for stroke is typically insufficient to achieve minimal thresholds for a cardiorespiratory training effect.[8,9] Aerobic training intensity has been assessed 2 days a week beginning 2 weeks poststroke for patients receiving inpatient rehabilitation after stroke.[8] Based on a 2-day sample per week, patients achieved a training HR for less than 4 min per day. HR monitors and accelerometers have also been employed to assess walking-related changes in HR and walking bout duration for eight patients on a single day of inpatient rehabilitation for stroke.[9] It was reported that no patients met the minimum threshold for HR intensity, frequency, and duration to stimulate cardiorespiratory benefit.

Questions remain about whether wearable HR sensors might be feasibly employed to continually assess HR response throughout the inpatient rehabilitation stay and, if feasible, might produce different conclusions about a cardiorespiratory training effect than the sparse sampling of inpatient days in extant studies. The primary purpose of this study was to determine feasibility for continuous assessment of HR in inpatient rehabilitation and, in doing so, explore whether HR response reached the minimum intensity, frequency, and duration necessary for therapeutic aerobic benefit. The dynamics of HR response were recorded continuously and longitudinally during the inpatient stay using an accelerometry-based physical activity monitor with an onboard HR sensor worn day and night. To assess the feasibility of long-term data collection with this wearable device, we monitored the incidence of adverse events, namely device-acquired skin breakdown, pressure ulcers, or nosocomial infections, and the frequency of protocol deviations, namely subjects or clinical staff removing the sensor when instructed not to do so.

We used recommendations from the American Heart Association/American Stroke Association (AHA/ASA) to assess whether the HR response to rehabilitation activities was sufficient to elicit a beneficial cardiorespiratory training response.[10] The AHA/ASA recommends large muscle activities at a level of intensity sufficient to maintain HR within a zone equal to 55–80% of maximal estimated HR (target HR [THR]) for at least 10 continuous minutes for a total of at least 20 min a day 3–5 days per week. Activity intensity that causes HR to exceed 80% of maximal estimated HR is considered excessive workload that will limit continued exercise. We considered HR in this zone to be excessive HR (EHR).

Our study extended previous attempts to assess HR response in inpatient rehabilitation by more thoroughly monitoring HR response to any form of exercise across the inpatient rehabilitation stay and for a wider range of medical conditions than stroke.[8,9] We did not exclude patients utilizing beta-adrenergic blockade (BB) medications, which alter maximal HR. Instead, we adjusted calculations of maximal HR (HRmax) as a measure of intensity using an equation developed for patients on BB therapy.[11] We hypothesized that sustained HR increases during inpatient rehabilitation activities would not be sufficient to meet recommendations for obtaining a therapeutic effect. If our hypothesis is confirmed, results of this study will assist in planning a trial in which HR feedback from activity monitors is provided to clinicians within the therapy day to generate exercise bouts at the recommended intensity, frequency, and duration to achieve therapeutic benefit while avoiding frequent EHR bouts.

Materials and Methods

SUBJECTS

Subjects were 15 patients, 44 to 80 years of age, receiving inpatient rehabilitation services at a medical rehabilitation center. Across subjects, 97,800 min of HR data were analyzed. The specific medical diagnoses of the subjects were heterogeneous, as described in *Table 1*. Four subjects were on BB therapy. Patients were eligible for the study if they were able to ambulate, at a minimum, with assistance at study enrollment. All protocols were approved by the Institutional Review Board, and written informed consent was obtained from subjects before entry into the study.

DESIGN

The study utilized ecological momentary assessment to obtain activity metrics in a real-world clinical environment. Subjects and their clinicians were informed that this was an observational study and that therapeutic activities were to carry on using typical standard of care. Neither subjects nor clinicians were informed that HR data would be analyzed, and HR data were not shared with patients or clinicians. Patients were recruited into the study within 48 h of admission to the facility and exited the study on the day of discharge.

INSTRUMENTATION

Activity and HR were monitored with a wrist-mounted three-axis accelerometer (Fitbit Charge HR™). A wrist-worn sensor was chosen over a waist- or ankle-mounted sensor to measure HR. HR was measured through photoplethysmography to establish green light absorption by blood within the wrist with photodiodes as the volume of blood in the wrist changed. Moderately strong correlations between HR measurement with the sensor and electrocardiogram have been obtained in healthy adults during various degrees of physical effort from rest to vigorous activity (r range = 0.81–0.83).[12,13] The sensor has been reported to underestimate HR by a small margin (3.4%)

Table 1. Subject Characteristics and Intensity, Duration, and Frequency of Target Heart Rate Events During Inpatient Stay

SUBJECT	AGE (YEARS)	SEX	REHABILITATION IMPAIRMENT CATEGORY	LENGTH OF STAY (DAYS)	ADMISSION FIM MOTOR SCORE	DISCHARGE FIM MOTOR SCORE	PERCENT OF DAYS MEETING ALL THR RECOMMENDATIONS (GOAL = 42% OF HOSPITAL DAYS)[a]	MEAN DURATION OF LONGEST THR BOUT EACH DAY (MIN)	STANDARD DEVIATION OF LONGEST THR BOUT EACH DAY (MIN)
1	75	M	Orthopedic disorder	10	56	83	100	25	8
2	46	F	Stroke	13	54	85	30	13	22
3	74	F	Pulmonary disorder	19	35	79	88	117	60
4	48	M	Cardiac disorder	21	59	84	67	31	30
5[b]	55	M	Debility	11	50	69	100	53 (230)	25 (94)
6[b]	59	M	Medically complex condition	14	51	84	91	11 (55)	12 (43)
7	68	M	Stroke	11	55	84	33	9	9
8	50	F	Stroke	8	56	86	0	9	11
9	80	F	Lower extremity fracture	10	44	59	100	34	22
10	60	F	Stroke	11	37	63	0	0	0
11	74	F	Stroke	19	49	70	100	109	76
12[b]	61	M	Stroke	11	60	83	100	64 (140)	49 (43)
13[b]	78	M	Cardiac disorder	8	53	86	100	2 (132)	5 (34)
14	48	F	Stroke	28	37	75	0	0.4	2
15	44	M	Stroke	7	56	81	0	0	0
Average	61			13	50	78	61	32 (139)	22 (54)

Values in parentheses are adjusted for patients on beta-adrenergic blockade therapy based on the maximal heart rate formula derived by Brawner et al.[11] Values not in parentheses for subjects on beta-adrenergic blockade therapy are based on the formula derived by Tanaka et al.[15]

[a]At least two 10-min bouts per day in the target heart rate zone on at least 42% of hospital days.

[b]Subject on beta-adrenergic blockade therapy.

FIM, Functional Independence Measure; THR, target heart rate.

compared with the electrocardiogram during slow to moderate speed walking (2 and 3.5 km/h).[14]

PROCEDURES

The sensor was attached to the wrist 2 cm above the styloid process of the radius so that it was securely in contact with the skin, but not tight enough to restrict blood flow. The dominant arm was used unless that arm was hemiplegic, in which case the nondominant arm was used. The sensor was worn day and night, even while showering, to quantify HR per 24-h period. We analyzed HR data during the period in which therapy services (physical, occupational, speech, or recreational) would be scheduled (07:00–17:00 h). The sensor was changed every 5 days for battery charging and to download data.

DATA ANALYSES

Graded exercise testing to derive an individual HRmax is not customarily employed in inpatient rehabilitation settings because patients are typically limited by motor or cognitive impairment. In lieu, age-adjusted prediction equations can be used to estimate HRmax. HRmax was estimated from the formula derived by Tanaka et al.[15] for sedentary men and women ranging in age from 18 to 81 years: $(212 - 0.7 \times \text{age})$. For patients taking BB medications, a secondary HRmax was calculated to account for the suppressive effect of BB therapy on HR with the following equation: $164 - 0.7 \times \text{age}$.[11]

Minute-by-minute time series of HR were analyzed. The days that the sensor was attached and removed were not included in analyses since the sensor was only worn for a portion of these days. Intensity was quantified as the percentage of HRmax within 1-min data collection bins from the HR time series. Intensity was considered to be in the THR zone sufficient to obtain cardiorespiratory benefit when the 1-min bin value was 55% to 80% of HRmax. HR was considered to be excessive if the bin value exceeded 80% of HRmax. Duration of HR within the THR zone was quantified as the number of consecutive minutes of HR within the zone. The frequency of HR bouts in the THR of at least 10-min duration was summed per day. Because most participants had lengths of stay (LOS) that were not multiples of 7, we divided days meeting the recommendations for THR by LOS to derive a frequency metric. When the frequency metric exceeded 0.42 (obtained by dividing the recommendation of a minimum of 3 days per week by 7), participants were considered to have met the recommendation for days per week exercising in the THR. Duration of EHR was quantified as the number of consecutive minutes of HR above the THR zone. The frequency of EHR bouts, regardless of duration, was summed per day.

The ability to predict characteristics of THR and EHR from demographic characteristics of age, sex, LOS, and motor function at admission and discharge using the Functional Independence Measure was explored. First, zero-order Pearson correlations were obtained, and if significant linear relationships were detected among demographic variables and characteristics of THR and EHR, demographic variables were included as predictors in multiple linear regression analyses. Normal probability plots of the residuals were examined to assess the regression assumption of normally distributed residuals. Independent *t* tests were employed to compare differences in age, LOS, and motor function at admission and discharge among those achieving THR goals versus not achieving such goals. Chi-square analyses analyzed the distribution of males and females achieving/not achieving THR goals.

Feasibility of long-term data collection with wrist-worn sensors was assessed through the incidence of device-acquired skin breakdown, pressure ulcers, or nosocomial infections and the frequency of protocol deviations in which subjects or staff removed the sensor.

Results

ANALYSES OF THR DATA

Table 1 displays results of analyses of THR data. Sixty percent of subjects (9/15) met all aspects of the recommendation of at least two 10-min bouts in the THR zone on at least 42% of hospital days, including the four patients on BB therapy. Six of nine subjects (67%) met the recommendation on 100% of hospital days. Thirteen percent of subjects (2/15) had at least two 10-min bouts in the THR zone on 30% to 33% of hospital days. One subject had single 10-min bouts in the THR zone on 50% of days. Twenty percent of subjects (3/15) had no 10-min bouts on any day.

Marked differences among subjects existed for the mean duration of the longest bout per day in the THR zone (*Table 1*). Likewise, standard deviations for longest daily bouts in the THR zone revealed marked day-to-day variability within subjects. When THR zones were adjusted downward for subjects on BB therapy, excessively long mean THR bout durations were noted (mean duration = 139 min).

Pearson correlation analyses between demographic characteristics and THR variables revealed age to be the single demographic variable sharing a significant linear relationship with percent of days meeting all recommendations. Linear regression using age to predict percent of days meeting all recommendations yielded an $R = 0.67$ ($p = 0.006$) and a standard error of estimate of 0.34. A normal probability plot of the residuals revealed strong linearity with residuals tightly concentrated about the plot reference line, indicating that regression assumptions were met. No demographic characteristics shared significant linear relationships with mean duration of the longest bout per day in the THR zone or standard deviation of the longest daily bouts in the THR zone (range of r values = 0.42 to −0.22, all p values ≥0.12). Those achieving THR goals were significantly older than those not achieving such goals (67.1 ± 11.5 vs. 52.7 ± 9.4 years of age, $p = 0.02$); however, groups did not differ on LOS or motor function at admission and discharge. The distribution of males and females in each group did not differ ($p = 0.32$).

ANALYSES OF EHR DATA

Table 2 displays results of analyses of EHR data. Forty-seven percent of subjects (7/15) experienced at least one daily episode in which HR exceeded the THR zone. The patient with lower extremity fracture experienced the greatest proportion of days with an EHR episode (62% of days). When the EHR threshold was adjusted downward for the four patients on BB therapy, two additional subjects experienced EHR episodes, bringing the proportion experiencing at least one daily episode in which HR exceeded the THR zone to 60% (9/15). For subjects not on BB therapy who experienced EHR, the duration of the longest EHR bout across all days ranged from 1 to 16 min. For subjects on BB therapy, when the adjustment to HRmax was applied to reduce the boundaries for THR, excessively long EHR bout durations were noted (mean duration = 55 min). Pearson correlation analyses revealed no demographic characteristics sharing significant linear relationships with EHR events (range of r values = 0.36 to −0.45, all p values ≥0.19).

Table 2. Frequency and Maximal Duration of Excessive Heart Rate Events During Inpatient Stay

SUBJECT	AGE (YEARS)	SEX	REHABILITATION IMPAIRMENT CATEGORY	PERCENT OF DAYS WITH EHR EVENTS	LONGEST DURATION OF AN EHR EVENT (MIN)
1	75	M	Orthopedic disorder	14	1
2	46	F	Stroke	0	0
3	74	F	Pulmonary disorder	50	6
4	48	M	Cardiac disorder	11	5
5[a]	55	M	Debility	0 (100)	0 (50)
6[a]	59	M	Medically complex condition	45 (91)	5 (38)
7	68	M	Stroke	11	1
8	50	F	Stroke	0	0
9	80	F	Lower extremity fracture	62	16
10	60	F	Stroke	0	0
11	74	F	Stroke	0	0
12[a]	61	M	Stroke	11 (100)	2 (121)
13[a]	78	M	Cardiac disorder	0 (100)	0 (12)
14	48	F	Stroke	0	0
15	44	M	Stroke	0	0
Average	61			14 (98)	2.4 (55)

Values in parentheses are adjusted values for patients on beta-adrenergic blockade therapy based on the maximal heart rate formula derived by Brawner et al.[11]

[a]Subject on beta-adrenergic blockade therapy.

EHR, excessive heart rate.

FEASIBILITY ANALYSES

No cases of device-acquired skin breakdown, pressure ulcers, or nosocomial infections were noted. In addition, protocol deviations in which subjects or staff removed the sensor were not reported.

Discussion

This study utilized commercially available activity monitors to measure HR continuously throughout inpatient rehabilitation stays for patients with a variety of diagnoses. The majority of participants met the minimum cumulative requirements of aerobic intensity (55–80% of HRmax), duration (at least 10 min continuously for at least 20 min a day), and frequency (at least 42% of inpatient days) necessary for cardiorespiratory benefit. Of the minority of participants who did not reach a cardiac workload necessary to stimulate meaningful cardiovascular benefit, all were engaging in therapy for stroke. Individual differences in the level of cognitive and motor impairment with stroke might explain the variation in achievement of recommended targets among patients with stroke. Alternately, differences in standard of care among clinicians for the workload expected of patients recovering from stroke are also possible. Further study is warranted that provides HR feedback to the clinician within the therapy day to generate exercise bouts at the recommended intensity, frequency, and duration to achieve cardiorespiratory benefit.

Our findings illuminate and extend findings from previous attempts to quantify HR training response in inpatient rehabilitation among stroke patients.[8,9] Previous studies used sparse sampling of inpatient days for stroke to draw the conclusion that cardiac workload was insufficient to achieve THR recommendations. Contrary to these studies, we illustrate that patients can achieve THR recommendations in inpatient rehabilitation for many different rehabilitation conditions, including stroke. This finding illustrates the importance of employing continuous data collection methods to characterize cardiac workload across the inpatient stay with greater precision.

The propensity to achieve THR recommendations was not associated with specific rehabilitation conditions, patient sex, LOS, or functional status at admission or discharge. However, regression analyses revealed that the greater the patient age, the greater the proportion of days meeting THR recommendations. Notably, subjects who did not achieve THR for the recommended number of days were significantly younger than those who did meet THR recommendations. This finding was unexpected and suggests that clinical staff may particularly benefit from HR feedback for younger patients to achieve greater levels of cardiorespiratory workload. Aside from age, correlational analyses suggest that other factors that we did not measure may be associated with meeting recommended cardiorespiratory targets, such as patient motivation and capacity for work, and therapist tendencies to urge patients to work on activities that challenge cardiorespiratory endurance.

Analyses of duration of bouts in the THR zone revealed substantial between-subject differences. Individual means for the longest daily bouts in the THR indicated that some subjects were working extremely hard for extended periods during the therapy day, while others had minimal cardiorespiratory challenge. Within-subject variability of the longest THR bout day-to-day was also markedly large for patients achieving THR recommendations, suggesting that days with lower cardiac demands were interspersed with days in which cardiac workload was high. Future studies could utilize wearable sensors to inform clinicians of the pattern of cardiac workload across days to find the most effective dose of days meeting THR recommendations balanced with days of less relative cardiac workload to avoid excessive fatigue.

For patients on BB therapy, the mean daily duration of bouts in the THR zone was exceedingly high, signaling that these patients may have had poor HR recovery following activity that taxed the cardiovascular system. The potential also exists that the equation validated for use in this population is overly conservative in its estimate of the HR necessary to stimulate cardiorespiratory benefit.[11] The reported standard error of estimate was 18 beats,[11] which equates to an individual margin of error at the 68% level of confidence of 36 beats per minute. It is therefore difficult to draw conclusions from our analyses of patients on BB therapy given the high probability for error in estimates of THR and EHR. Further work would be beneficial to determine whether an equation could be developed for use in the population on BB therapy that has a smaller margin of error. In addition, the current study appears to be the initial empirical test of HR training response for patients on BB therapy relative to AHA/ASA recommendations.[10] Future studies could examine recommendations in a larger cohort of patients on BB therapy to understand whether specific adjustments to recommendations for this population are in order.

Fifty-three percent of participants had no EHR events, suggesting that cardiac workload was unlikely to limit participation in most patients. Conditions were varied for the 47% of patients who exceeded 80% of THR: orthopedic disorder, pulmonary disorder, cardiac disorder, medically complex condition, lower extremity fracture, and stroke. Four of seven patients experienced an EHR bout on a single day, with the duration of the bout lasting 1 to 5 min.

This is the initial study to illustrate that collection of HR data continuously throughout an inpatient rehabilitation stay using wearable sensors is feasible. There were no adverse events reported from long-term use and no protocol deviations from patients or staff removing the sensors. Our findings on HR are illustrative of the utility of wearable sensors for providing longitudinal clinically meaningful information. Thus, while most commercially available activity monitors are not approved as medical devices, devices with HR measurement capability have utility for providing long-term objective feedback about HR response in inpatient rehabilitation.

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Disclosure Statement

No competing financial interests exist.

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