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Measuring Physical Activity With Implanted Cardiac Devices: A Systematic Review

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***Background*—**Physical activity is predictive of cardiovascular outcomes in patients with cardiovascular implantable electronic devices, yet it is not regularly assessed in routine care. Current-generation cardiovascular implantable electronic devices, however, continuously monitor patient activity through a built-in accelerometer, which provides new opportunities to remotely assess patient activity, detect changes in clinical status, and incorporate these data in risk stratification models. This review critically examines the literature on device-measured physical activity (D-PA), with a focus on identifying methodological issues that may affect interpretation of study results.

***Methods and Results*—**We conducted a systematic review of D-PA studies published from January 1 1995 to December 30 2017, identifying 29 studies meeting inclusion criteria, 5 of which were validation reports. Few technical details about D-PA sensors are reported, and procedures for analyzing and interpreting D-PA data are heterogeneous. Trends in D-PA over time and associations with clinical outcomes were reported by 22 studies, and in 7 studies, D-PA was combined with other device parameters in risk stratification models, demonstrating modest-to-good sensitivity in predicting acute heart failure decompensation, hospitalization, and mortality.

***Conclusions*—**Current evidence suggests that D-PA may be useful for assessing physical activity and predicting clinical outcomes in patients with cardiovascular implantable electronic devices when combined with other device parameters. Future work must address challenges related to D-PA data measurement, interpretation, and generalizability to support expanded clinical applications of this technology. **(*J Am Heart Assoc*. 2018;7:e008663. DOI: 10.1161/JAHA.118.008663.)**

Key Words: accelerometer • cardiovascular implantable electronic device • device-derived activity • exercise • implantable cardioverter-defibrillator • physical activity

Moderate leisure-time physical activity is safe and clinically recommended for most patients with cardiovascular implantable electronic devices (CIEDs) (ie, implantable cardioverter-defibrillators [ICDs], cardiac resynchronization therapy [CRT], and pacemakers).[1] The benefits of regular physical activity for secondary prevention are also well established,[2] and for patients with ICDs in particular, participation in exercise training programs may reduce their risk for ICD shock.[3,4] Alternatively, declines in activity may signal a change in clinical status in patients with heart failure (HF).[5]

In addition to providing life-saving therapies for tachyarrhythmias and bradyarrhythmias, modern CIEDs are capable of continuously monitoring patients' cardiac rhythm (eg, atrial fibrillation [AF] burden and percentage pacing) and measuring intrathoracic impedance to guide HF management, as well as storing these data.[6] Most implanted devices also automatically collect and store daily physical activity data obtained from an internal accelerometer, incorporated for the primary purpose of rate-responsive pacing.[6] As the patient moves or accelerates, piezoelectric crystal sensors detect changes in the frequency and amplitude of body motion,

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Accompanying Tables S1, S2 and Figure S1 are available at http://jaha.ahajournals.org/content/7/11/e008663/DC1/embed/inline-supplementary-material-1.pdf

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Clinical Perspective

What Is New?

- Current-generation cardiovascular implantable electronic devices continuously collect and store daily physical activity data through a built-in accelerometer, providing new opportunities to remotely assess patient activity, detect changes in clinical status, and incorporate these data in risk stratification models.
- This systematic review summarizes findings from 29 published studies on device-measured physical activity, including 5 validation reports.
- Available evidence suggests that device-measured physical activity may be useful for assessing physical activity and predicting clinical outcomes in patients with cardiovascular implantable electronic devices when combined with other device parameters.
- However, numerous methodological issues related to device-measured physical activity data measurement, interpretation, and generalizability were identified and warrant further attention.

What Are the Clinical Implications?

- These findings support the need for future prospective studies and randomized clinical trials to inform expanded clinical applications of this technology.

generating an electrical signal that is proportional to patient movement.[6] Proprietary algorithms then analyze, encrypt, and store device-measured physical activity (D-PA) data in device memory, which can be downloaded during routine clinic visits or through remote monitoring.

The potential of the accelerometer feature to assist clinicians in monitoring patient activity longitudinally, detect changes in functional status, and proactively deliver care to prevent adverse events is of great interest and is under active investigation. In preliminary studies, D-PA has been shown to independently predict ventricular reverse remodeling, hospitalization, and mortality.[7] In patients with CRT with HF, D-PA predicts nonfatal ventricular tachyarrhythmias and short-term HF events.[8] D-PA data have also been combined with other diagnostic parameters in risk stratification models to predict acute HF decompensation, hospitalization, and mortality.[9–14] However, the specific methods used to measure, analyze, and interpret D-PA data are not fully described, and they vary considerably between studies. This variation in approach hinders the ability to compare data or synthesize findings, thereby limiting current clinical applications of D-PA.

We conducted a systematic review of published reports on D-PA and identified methodological issues that may affect interpretation of study results. In addition, we provide recommendations for how to strengthen the evidence base for D-PA and articulate a framework for how these data could be used to modernize activity measurement in clinical trials and outcomes research and potentially improve evaluation and management of patients with CIEDs.

Methods

Literature Search Strategy and Selection Criteria

This systematic review was performed in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analyses guidelines (Figure S1).[15] The data, analytic methods, and study materials will not be made available to other researchers for purposes of reproducing the results or replicating the procedure. We conducted a search of PubMed and the Cochrane databases to identify relevant studies published in peer-reviewed English-language journals from January 1 1995 to December 30 2017. A combination of predefined search terms was used: CIEDs ("implantable cardioverter defibrillator" or "cardiac resynchronization therapy" or "pacemaker" or "cardiovascular implantable electronic device") and "device-measured activity" or "physical activity" or "accelerometer" or "ICD diagnostic algorithm" or "heart failure device risk stratification model" or "device-derived activity." The reference lists from published articles were also examined, and potentially relevant articles were retrieved. Eligible studies included D-PA validation studies and clinical investigations. Abstracts, case studies, conference presentations, and articles published in non–peer-reviewed journals were excluded from this review.

Results

Summary of Published Findings

As of December 2017, we identified 29 published studies that included D-PA, conducted primarily in the United States and Europe. Characteristics of the 29 studies are reported in the Table. More than half (n=17 [59%]) reported on D-PA data obtained from Medtronic devices, followed by Boston Scientific (n=9 [31%]) and Biotronik (n=2 [7%]). One study compared D-PA from 2 manufacturers (Medtronic and St Jude).[7] Three quarters (n=22) reported on D-PA trends over time and associations with clinical end points, whereas one quarter (n=7) evaluated D-PA as a component integrated with other device-based diagnostic parameters in risk prediction models. With the exception of validation studies (n=5), which generally involved smaller samples, most published reports included ≥100 patients in their sample. Women, on average, represented 27% of patients in each study cohort. Only one study examined D-PA in patients with pediatric devices.[16] Twenty-one studies included only patients with HF, whereas 8

Table. Summary of Studies That Examined Device-Measured Physical Activity

Study	Sample Size, N	Device Type; Manufacturer*	Study Design	Cardiac Pathological Features	Mean Age, y	Women, %	Follow-Up, mo†	End Points
Adamson et al, 2004[9]	397	CRT; Medtronic	Secondary analysis of data from RCT	HF	Reported for 3 subgroups: 66±11, 65±12, 66±9	42	Reported for 3 subgroups: 16.6±4.0, 16.9±4.3, 12.6±5.7	D-PA added to risk model predicted HF decompensation and hospitalization (S); D-PA declined in the weeks before hospitalization for acute decompensated HF (S)
Braunschweig et al, 2005[18]	56	CRT; Medtronic	Observational cohort study	HF	66±11	17.9	4	D-PA increased during first month after implantation (S) and continued to increase in NYHA functional class II (S) but remained stable in functional classes III and IV at 4 and 12 wk. NYHA functional class IV was the least active at 12 wk (S)
Boehmer et al, 2017[10]	900	CRT-D; Boston Scientific	International multicenter nonrandomized study	HF	66.8 10.3	28	12	Developed risk prediction model for HF decompensation; final model detected 70% of worsening HF events a median of 34 d before the event
Chelu et al, 2016[19]	266	ICD; Medtronic	Retrospective observational cohort study	Persistent AF	69±10.2	12	4.3±1.5 y	D-PA declined at the onset of persistent AF, remained low during AF, and returned to baseline levels in 85% of patients 12 wk after AF termination (S); patients with low AF burden (<6 h/d) returned to their baseline activity faster than patients with a higher AF burden (>6 h/d)
Conraads et al, 2014[11]	781	CRT-D and ICD; Medtronic	Secondary analysis of pooled data from RCTs	HF	65±10	15	15±7	Developed risk prediction algorithm for HF hospitalization and mortality. Mean 30-d D-PA predicted HF hospitalization (HR, 0.97) and all-cause mortality (HR, 0.93) (S); 10 min/d of additional activity associated with 4% reduction in mortality risk (HR, 0.95). Adding D-PA to CHARM risk model for HF improved risk stratification (S)

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Table. Continued

Study	Sample Size, N	Device Type; Manufacturer*	Study Design	Cardiac Pathological Features	Mean Age, y	Women, %	Follow-Up, mo†	End Points
Cowie et al, 2013[12]	2231‡	CRT-D; Medtronic	Secondary analysis of pooled data from RCTs	HF	68±11	31	10.6±5.8	Developed risk prediction model for HF hospitalization. In the validation data set, D-PA was associated with a 2.5-fold increase in 30-d risk for HF hospitalization (S); D-PA combined with other diagnostic data predicted HF hospitalization
de la Uz et al, 2017[16]	1905	ICD and pacemaker; Medtronic	Observational study	Pediatric device patients	Median age, 14 y; interquartile range, 12–16 y	38.7	28 d	Mean activity was 5.4 (SD, 2.0) h/d. Increased activity was associated with being a man, having a pacemaker, epicardial device location, rate response turned off, having experienced a shock, and younger age (S)
Gilliam et al, 2007[20]	1421	CRT-D; Boston Scientific	Observational registry study	HF	69.3±11	21.8	12	D-PA increased over time (S); mean D-PA was lower in patients >70 y old compared with those <70 y old (S)
Jamé et al, 2017[8]	1008	CRT-D; Boston Scientific	Secondary analysis of data from RCT	HF	NR	25	≥26 wk	Decline in D-PA of >40% was short-term predictor of mortality, HF events, and ventricular tachyarrhythmias in adj and unadj models (S)
Kadhiresan et al, 2002[21]	30	CRT; Boston Scientific	Validation study using data from RCT	HF	60±6	50	3	D-PA was positively correlated with the 6MWT (S), demonstrating 84% sensitivity and 73% specificity to detect changes in distance walked from baseline to 12-wk follow-up
Kawabata et al, 2007[22]	178	CRT and CRT-D; Boston Scientific	Observational cohort study	HF	65±8	20	21.9±11.6	Younger age (<65 y) was associated with increased D-PA (S), whereas the associations between D-PA and ischemia, permeant AF, and diabetes mellitus were NS; baseline D-PA was higher in patients with device replacement compared with de novo implantations (S)

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Table. Continued

Study	Sample Size, N	Device Type; Manufacturer*	Study Design	Cardiac Pathological Features	Mean Age, y	Women, %	Follow-Up, mo†	End Points
Kramer et al, 2015[23]	98 437	CRT-D and ICD; Boston Scientific	Observational registry study	All patients with CIEDs	67.7±13.1	28.9	Median of 2.2 y	Baseline and time-varying D-PA predicted survival; 4-y survival was highest in most-active quintile (S); 30 min/d less activity in a given month associated with a 48% increase in mortality risk (S)
Kramer et al, 2017[24]	26, 509	CRT-D; Boston Scientific	Observational registry study	HF	70.2±11.0	29.3	Median of 2.3 y	Activity increased from baseline to 6 mo (S) for most patients (activity did not improve or declined in 15.5% of patients); activity change from baseline to 6 mo predicted 3-y survival (S); in adj models, higher 6-mo activity change was associated with a lower mortality risk (HR, 0.65 per 30-min increase in activity) (S); patients in the highest vs lowest quintiles of 6-mo D-PA change were younger and were less likely to have a prior ICD (S)
Kramer et al, 2017[25]	219	ICD, pacemaker, and implantable loop recorder; Boston Scientific	Observational registry study	All patients with CIEDs	68±13	30	≥7 d	D-PA associated with mobility and frailty in adj and unadj models (S)
Melczer et al, 2016[26]	17	CRT and CRT-D; Biotronik	Validation study	HF	57.4±9.5	17.6	7 d	Daily D-PA data (PA % values) correlated weakly (r=0.37) with MET values derived from ActiGraph GT3X+ (r=0.37)
Pressler et al, 2013[27]	73	ICD and CRT; Medtronic	Validation study	HF	60±20	21	7 d	Study showed strong intraindividual correlation between D-PA and AiperMotion 440§ (r>0.7); total daily activity measured by both devices differed (S)

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Table. Continued

Study	Sample Size, N	Device Type; Manufacturer*	Study Design	Cardiac Pathological Features	Mean Age, y	Women, %	Follow-Up, mo†	End Points
Sears et al, 2015[28]	174	ICD and CRT; Medtronic	Secondary analysis of data from RCT	All patients with CIEDs	62±13	17	1	Median D-PA was low (22.5 h/wk); D-PA declined after ICD shock (S) but not ATP therapy; association between D-PA and the number of ATP therapies was NS, whereas D-PA significantly declined after ICD shock, and that as the number of shocks increased, D-PA decreased (S); 5≥ shocks was associated with the largest decline in D-PA (S)
Sears et al, 2017[29]	2790	ICD and CRT; Medtronic	Secondary analysis of data from RCT	All patients with CIEDs	65±12	21	24	D-PA declined after ICD shock (−23.7 min/d when corrected for device type, time since implantation, and the effect of hospitalization) (S), and gradually recovered to a normal level after ≈90 d. D-PA was inversely associated with the number of prior shocks, such that more shocks led to a greater decline in D-PA. Type of shock therapy (appropriate vs inappropriate) was not associated with D-PA
Sharma et al, 2015[30]	775	CRT-D; Medtronic	Secondary analysis of pooled data from RCTs	HF	69±11	32	13±5	Developed model to predict 30-d risk for HF hospitalization; D-PA was associated with a 5.1% HF hospitalization event rate in unadj models
Shoemaker et al, 2017[31]	16	ICD and CRT-D; Medtronic	Validation study	HF	64.9±11.3	43.7	3	Moderate-to-strong correlations between D-PA and Actigraph GT3X were reported for hours of activity/day, steps/day, and changes in activity over time (S); D-PA underestimated activity by 0.80 h and CIs were large; most patients with ICDs engaged in <15 min/wk of moderate-intensity activity (measured by the Actigraph GT3X)

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Study	Sample Size, N	Device Type; Manufacturer*	Study Design	Cardiac Pathological Features	Mean Age, y	Women, %	Follow-Up, mo†	End Points
Shoemaker et al, 2012[32]‖	102	CRT-D and ICD; Medtronic	Retrospective medical record review	HF	64.6±13.3	29.4	7.5	D-PA moderately correlated with 1- and 5-y mortality (S)
Shoemaker et al, 2016[33]‖	16	ICD and CRT; Medtronic	Secondary analysis of data from RCT	HF	66±14	43.8		Association between seasonal weather change and daily D-PA (NS)
Shoemaker et al, 2013[34]‖	102	ICD; Medtronic	Secondary analysis of data from a retrospective observational study	HF	64.6±13.3	29.4	6	Described 4 patterns of daily D-PA, ranging from low (<30 min/d) to high (>360 min/d); activity patterns remained stable over time; D-PA associated with age, NYHA functional class, female sex, and LVEF (S)
Small et al, 2009[35]	326	CRT-D; Medtronic	Multicenter retrospective cohort study	HF	70±11	25.0	333±97 d	Association between low D-PA (<30 min) and hospital admissions for acute decompensated HF was NS
Singh et al, 2009[13]	1206	CRT-D; Boston Scientific	Secondary analysis of pooled data sets	HF	66.8±11.8; 67.6±11.2	21.7	Median of 18 mo	D-PA combined with device diagnostissc data predicted mortality (S)
Tyagi et al, 2015[17]	96	Pacemaker; Medtronic	Retrospective medical record review	Preserved left ventricular function	NR	NR	4.1±2.2 y	All-cause mortality increased as active minutes per day decreased (S); in adj analyses, low activity (<1 h/d) was associated with a 7.4-fold increase in mortality during follow-up compared with those engaging in activity >3 h/d (S)
Vegh et al, 2014[7]	164	CRT; Medtronic and St Jude	Validation study	HF	67.3±12.9	23.0	Median of 18 mo	D-PA was moderately correlated with the 6MWT (S); D-PA predicted HF hospitalizations, mortality, and ventricular reverse remodeling (S); one additional hour of activity at 1 mo was associated with a 1.38-fold improvement in echocardiographic response (S)
Whellan et al, 2010[14]	694	CRT-D; Medtronic	Prospective observational cohort study	HF	68.4±10.7	32.7	11.7±2.0	D-PA combined with HF device diagnostic data predicted risk of HF hospitalization within the next 30 d in unadj (HR, 5.5) and adj (HR, 4.8) models (S)

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Table. Continued

Study	Sample Size, N	Device Type; Manufacturer*	Study Design	Cardiac Pathological Features	Mean Age, y	Women, %	Follow-Up, mo†	End Points
Zhao et al, 2017[36]	845	CRT-D and ICD; Biotronik	Retrospective observational registry study	All patients with CIED	60.4±14.4	26.3	31.1 ± 12.9	D-PA ≤113 min/d predicted all-cause mortality in unadj (HR, 4.1) and adj (HR, 3.6) models and cardiac death in unadj (HR, 4.1) and adj (HR, 3.7) models (S); D-PA correlated well with HRV (r=0.6) (S)

6MWT indicates 6-minute walk test; adj, adjusted statistical models; AF, atrial fibrillation; CHARM, Candesartan in Heart Failure–Assessment of Mortality and Morbidity; CI, confidence interval; CIED, cardiovascular implantable electronic device; CRT, cardiac resynchronization therapy; CRT-D, CRT defibrillator; D-PA, device-measured physical activity; HF, heart failure; HR, hazard ratio; HRV, heart rate variability; ICD, implantable cardioverter-defibrillator; LVEF, left ventricular ejection fraction; MET, metabolic equivalent value; NR, not reported; NS, statistically nonsignificant; NYHA, New York Heart Association; RCT, randomized clinical trial; S, statistically significant (P≤0.05); and unadj, unadjusted statistical models.

*Device manufacturers: St Jude Medical device (St Jude Medical Inc, Sylmar, CA), Medtronic (Medtronic Inc, Minneapolis, MN), Boston Scientific CRM (formally Guidant Corporation), and Biotronik (Biotronik, Berlin, Germany).

†Data presented as mean±SD months unless otherwise indicated.

‡Study sample included patients from a development data set (N=921) and a validation data set (N=1310).

§AiperMotion 300 PFH (Aipermon GmbH & Co KG, Munich, Germany).

‖Study measured D-PA by conducting a "visual estimation" of mean daily activity obtained from graphs of "Patient Activity" in Medtronic Cardiac Compass device reports.

studies included patients with all devices regardless of cardiac pathology. One study specifically focused on patients with pacemakers and preserved left ventricular function.[17] Nearly half of the studies were secondary analyses of clinical trial data (n=12 [41%]). A more detailed discussion of findings from selected studies is provided later, according to activity trends over time and clinical end points.

Measurement of D-PA by Device Manufacturer

Although the sensor mechanisms involved in ambulatory activity monitoring are relatively similar across device manufacturers, there is considerable variation between companies about how activity data are analyzed, encrypted, stored, and interpreted. In many cases, investigators report few technical details about the accelerometer activity sensor thresholds or signal processing algorithms used in specific CIEDs to quantify activity. Descriptions of D-PA data analysis procedures are also limited, but we provide the information that is available in published reports (Table S1).

Validation Studies

Five validation studies were reported.[7,21,26,27,31] These studies enrolled fewer patients, had a higher percentage of women, and had a shorter duration of follow-up than the clinical investigations described later.

In 3 studies, D-PA from CIED accelerometers was compared with data from validated external devices. Two studies used the Actigraph GT3X external accelerometer as the comparison to D-PA. One study[31] found that D-PA data from Medtronic CIED correlated strongly (r=0.83) with activity data from the Actigraph, whereas the other study[26] found that D-PA from Biotronik CIED correlated only weakly (r=0.37) with metabolic equivalent values derived from Actigraph. In a third study, D-PA from Medtronic CIEDs was compared with activity data from the AiperMotion 440 external accelerometer, and although strong *intraindividual* correlations were reported, there were substantial differences in the total amount of daily activity recorded by the devices.[27] As noted by the authors, variation in activity captured by implanted versus external accelerometers may be attributable to differences in device placement (pectoral implant versus hip- or wrist-worn accelerometers) and type of activity. It is also possible that external triaxial accelerometers, which use 3-dimensional measurements to quantify activity, may be better able to discriminate between ambulatory and nonambulatory movement compared with the single-axis accelerometers in implanted devices.[27]

Two studies examined the validity of Medtronic and Boston Scientific CRT devices in assessing exercise capacity in ambulatory patients with HF. Both studies compared D-PA with the 6-minute walk test (a validated measure of exercise

capacity and a strong independent predictor of clinical outcomes in patients with HF[5]) to determine whether D-PA could potentially serve as a marker of functional status in these patients.[7,21] Both investigations showed that D-PA moderately correlated with 6-minute walking distance (r=0.35–0.49). Furthermore, in multivariate models, D-PA and the 6-minute walk test demonstrated similar utility as a univariate predictor of clinical response to CRT.[7] These findings suggest that D-PA may be a valid and reliable indicator of clinical status in patients with HF. Moreover, because CIED accelerometers provide continuous objective activity data in real time, D-PA might be more clinically useful for assessing functional status than the 6-minute walk test, which can only assess functionality at a particular point in time.

In summary, 4 of 5 published validation studies showed that activity measured by D-PA was moderately correlated with external accelerometers and performed as well as an established measure of functional status in predicting intermediate outcomes among patients with CIEDs with HF. Nonetheless, these studies were conducted in small highly selective patient samples, and data are limited to activity detected during walking tasks. No validation studies have examined the accuracy of CIEDs to recognize movement that occurs during a wide range of patient activities (eg, stationary bicycling, swimming, gardening, and household chores) or compared activity detected by devices from multiple manufacturers.

Clinical Investigations

Activity trends over time

D-PA data are increasingly being used to understand patterns of activity engagement after ICD implantation; however, investigators have varied in the approach taken to calculate the baseline level of D-PA,[11,18,23,24,28,33,36] making it difficult to compare findings across studies. In some studies, baseline is defined as average activity over a period of several days, 1 to 2 weeks after CIED implantation,[18,22,24] to account for procedural recovery time; in other studies, baseline is defined as average activity over 7 to 30 days, 1 to 2 months after implantation.[11,23,28,36] Despite this variation in approach, D-PA at baseline is consistently low across studies (<3 hours of total activity per day), regardless of device manufacturer or sample characteristics.[23,24,28,36] As expected, D-PA was lowest immediately after device implantation and increased substantially over the next 90 days.[18,20,23,24,28,32,34] After 90 days, some studies showed that activity levels remained stable,[22–24] whereas other studies described a continued increase in D-PA for up to 6 months after implantation.[7,34] Interpretation of these findings is complicated by the variation in how and when baseline activity was determined.

D-PA and mortality

The association between D-PA and mortality has been a focus of considerable research. Seven studies examined the relationship between D-PA and all-cause mortality,[7,8,11,17,23,24,32,36] with one including both all-cause and cardiac mortality.[36] Of these studies, all reported a significant inverse association between D-PA and all-cause mortality in unadjusted and adjusted models. One study of patients with pacemakers and preserved left ventricular function[17] showed that all-cause mortality increased as daily D-PA decreased and that patients with lower D-PA at baseline (<1 hour of activity per day) had a 7.4-fold elevated mortality risk at follow-up, compared with those who were more active (>3 h/d). Early activity (average activity over the first month after implantation) was also found to be inversely associated with all-cause mortality and cardiac morality.[11,23,36] Although these data are suggestive, they are observational, and thus D-PA may have served as a marker for unmeasured factors contributing to mortality risk.

D-PA and hospitalization

On the basis of the known connection between physical activity and hospitalization in patients with HF,[37,38] attention has turned to device metrics, such as D-PA, to determine their potential value as clinical indicators of risk for hospitalization. Seven studies examined D-PA as a predictor for hospital admissions among patients with CIEDs with HF.[7,9,11,12,30,35] Using data primarily from Medtronic CRT devices (one study reported on both Medtronic and St Jude CRT devices[7]), all but one study found that as D-PA declined, risk for acute HF decompensation and hospitalization increased significantly during the same 30-day period. One multicenter retrospective cohort study of patients, however, found the association between "low D-PA" (<30 min/d) and HF hospitalization to be nonsignificant in both unadjusted and adjusted models.[35] This discrepant finding may reflect the different activity threshold used to define "low activity" in this study, which was considerably lower than the thresholds used in the other studies (<60–<113 min/d).[7,14,36] These data highlight an important shortcoming of data-driven categorization of continuous variables and support the need for evidence-based clinical thresholds for D-PA.

Clinical predictors of D-PA

Eight studies examined clinical and demographic predictors of D-PA. Of these studies, most have found that older adults, women, and those who are more frail engage in less daily activity than patients who are younger, men, and less frail.[20,23,25,34] Comorbidities, such as AF, diabetes mellitus, peripheral artery disease, stroke, and diuretic use at baseline, have also been associated with lower levels of D-PA in the months after CIED implantation.[11,36] In contrast, findings on

the relationship between activity and New York Heart Association functional class, left ventricular ejection fraction (%), device type, and ischemic cause have been inconsistent.[11,18,31,34,36] Taken together, the independent contribution of demographic and baseline clinical characteristics to D-PA remains poorly understood, and known risk factors for inactivity, such as chronic pain, osteoporosis, and depression, have not been examined.

Effect of arrhythmias and device therapies on D-PA

Three investigations examined the temporal relationship between D-PA and arrhythmias. Variation in daily D-PA before, during, and after an episode of persistent AF was examined in one study of patients with dual-chamber ICD.[19] Results showed that in most patients, D-PA declined at the onset of persistent AF, remained low during AF, and returned to baseline by 12 weeks after AF termination. Another study examined the short-term effects of ICD shock and ATP on D-PA trends over a 30-day period.[28] Results showed that D-PA significantly declined after ICD shock and that as the number of shocks increased, D-PA decreased. In contrast, D-PA did not significantly decline after ATP therapies.[28] Another longitudinal investigation of a large, multicenter, international cohort of patients with ICD prospectively examined the short-term and lasting effects of ICD shock on objective behaviors (ie, D-PA) and subjective quality-of-life outcomes (ie, self-reported quality of life and shock anxiety).[29] Results from this study showed that D-PA significantly declined after ICD shock (−23.7 min/d when corrected for device type, time since implantation, and the effect of hospitalization) and gradually recovered to a normal level after ≈90 days. Similar to the EMPIRIC (Comparison of Empiric to Physician-Tailored Programming of Implantable Cardioverter-Defibrillators) trial,[28] an inverse relationship between D-PA and the number of prior shocks was reported; however, as an extension of these findings, this investigation showed that activity reduction did not differ significantly between appropriate and inappropriate shocks.

D-PA in risk stratification models

Developing cost-effective tools to predict and potentially prevent clinical decompensation and hospitalization in patients with HF is a priority for patients, providers, and healthcare systems. Accordingly, in 7 studies, D-PA was combined with other clinical and device data to develop, test, and validate clinically useful tools for ambulatory risk assessment in patients with HF.[9–14,30] Nearly all risk assessment tools were developed retrospectively, using data from completed clinical trials, and study samples included predominantly older white men. Risk models were mostly developed to predict acute HF decompensation and hospitalization within a 30-day period, although 2 studies tested risk prediction models for HF hospitalization and all-cause mortality.[11,13] Of the 7 studies, all found that models including D-PA provided modest-to-good sensitivity in the prediction of hospitalization and/or death in patients with HF. Still, it remains to be seen whether device-based risk stratification models improve clinical outcomes in patients with CIEDs with HF. Moreover, because women and racial and ethnic minorities are underrepresented in published studies, the predictive value of D-PA–based risk models for these patient groups is unknown. This is concerning, because traditional cardiovascular risk assessment tools have been shown to underestimate risk in women and minority patients.[39,40]

Discussion

To our knowledge, this review is the first to examine the current state of the D-PA literature. The strengths and limitations of D-PA technology and extant research are summarized in Table S2. Most studies showed significant associations between D-PA and relevant clinical outcomes, and when combined with other device parameters, D-PA–based models improve ambulatory risk assessment in patients with HF. However, we identified important methodological challenges, including inconsistency in D-PA baseline measurement, observational/cohort study designs, infrequent use of relevant covariates, and homogeneous patient samples, that limit our ability to draw conclusions from the data, compare results between studies, or synthesize findings to inform clinical applications of this technology. Indeed, one of the most striking findings was that published studies provide relatively few technical details about how specific CIED accelerometers detect, analyze, and interpret activity data, and available information suggests that activity sensor thresholds and signal processing algorithms differ considerably between manufacturers. Thus, activity captured by one device may not reflect the same amount of activity captured by another device. Addressing these issues is critical to strengthening the evidence base for D-PA and supporting future clinical applications of this technology.

Recommendations and Future Directions

Moving forward, it is imperative that future investigations provide sufficient technical details about specific CIED accelerometers, including how motion is detected and analyzed by signal processing algorithms, and the methods used for D-PA data analysis. This will allow for replication and development of a standardized approach to D-PA use in clinical research and real-world applications. Second, validation studies need to be conducted in larger, more diverse, patient samples and examine a wide range of patient activities (eg, bicycling, swimming, and household chores) using devices from multiple manufacturers. This would enhance

generalizability of D-PA data. Third, patients with CIEDs are a heterogeneous population, and more research is needed to identify patient groups (eg, women, racial and ethnic minorities, patients without HF, and patients <50 years old) and critical events (eg, ICD shock and hospitalization) that increase risk for inactivity. This would help define the utility of D-PA as an outcome measure in clinical trials designed to increase activity in specific patient groups.

Prospective research is also required to define potential therapeutic targets for daily activity measured by CIED accelerometer, and clinical trials need to evaluate whether a rapid clinical response to a D-PA–defined reduction in activity prevents hospitalizations, improves survival, or reduces healthcare expenditures. These data will be critical to guide risk evaluation and treatment and to help educate patients about physical activity. On the other hand, D-PA may have the greatest value as a parameter combined with other clinical and device diagnostic data to identify patients at high risk for adverse events. As multiple-parameter device-based risk stratification tools continue to be developed and tested, issues related to clinical adoption and implementation also need to be considered (eg, choosing which risk model to use, who will use it, when to use it, and thresholds for intervention).

D-PA data are not currently provided directly to patients, which limits their clinical utility for engaging patients in their care, encouraging self-monitoring, or promoting health behavior change.[41] Nonetheless, these data *are* presently available to healthcare providers and routinely included in device interrogation reports. Providers could use these activity summaries to initiate clinically meaningful discussions and engage in shared decision making with their patients about the importance of physical activity and how to increase/maintain optimal levels of activity to achieve desired health and quality-of-life goals, the associated risks of certain types of activity (eg, competitive sports in those with contraindications), preventative strategies to minimize potential risks (eg, optimal medical therapy and activity recommendations on the basis of individual risk profile), and the benefits of regular physical activity for secondary prevention.[4]

Conclusions

Advances in device technology provide new opportunities to continuously monitor patient's physical activity and use these data to develop cost-effective resource-efficient strategies to proactively prevent patient decompensation and hospitalization. Preliminary data are encouraging, but issues of data accuracy and generalizability must first be addressed. Clinical trials are also needed to evaluate the utility of D-PA data alone or in combination with other clinical and device-based markers of disease, in predicting patient outcomes. This work will provide important insights into how to best use D-PA data to inform patient care, device guidelines, and future activity interventions.

Disclosures

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SUPPLEMENTAL MATERIAL

Table S1. Measurement of Physical Activity by Device Manufacturer*

Manufacturer†	Activity Measurement
Boston Scientific	D-PA is continuously recorded and interpreted by a proprietary algorithm to determine whether a patient is 'active' or 'not active' for a given minute. When patient acceleration exceeds a pre-set threshold of 25 milligravities - equivalent to an approximate walking speed of 2 miles per hour or energy expenditure of 2.8 METS– an "active minute" is recorded. Based on established MET level categories (activity ≤ 2.99 METs = light intensity),[1] D-PA measured by these devices is considered light-intensity activity. A mean value for the amount of time a patient is active each day is calculated and stored in device memory for up to 1 year.[2-10]
Medtronic	D-PA is continuously recorded and interpreted with a proprietary algorithm that calculates the total number of active minutes per day based on a pre-set threshold. Patient acceleration that is equivalent to a walking rate of approximately 70 steps per minute is considered an active minute. Since a stepping rate equal to 100 steps/minute is considered moderate-intensity physical activity,[1] D-PA measured by Medtronic CIEDs falls between light and moderate-intensity activity (e.g., walking at a slow pace). A summary score for total activity in minutes per day is automatically calculated and stored in device memory for up to 14 months.[11-28]
Biotronik and St. Jude	Less information is readily available concerning Biotronik and St.Jude devices, however, both describe time for which sensor input exceeds resting heart rate. In prior studies, Biotronik D-PA data are reported as the percentage of time a patient is active each day[29, 30] whereas St. Jude devices report daily activity in units of hours/day.[27]

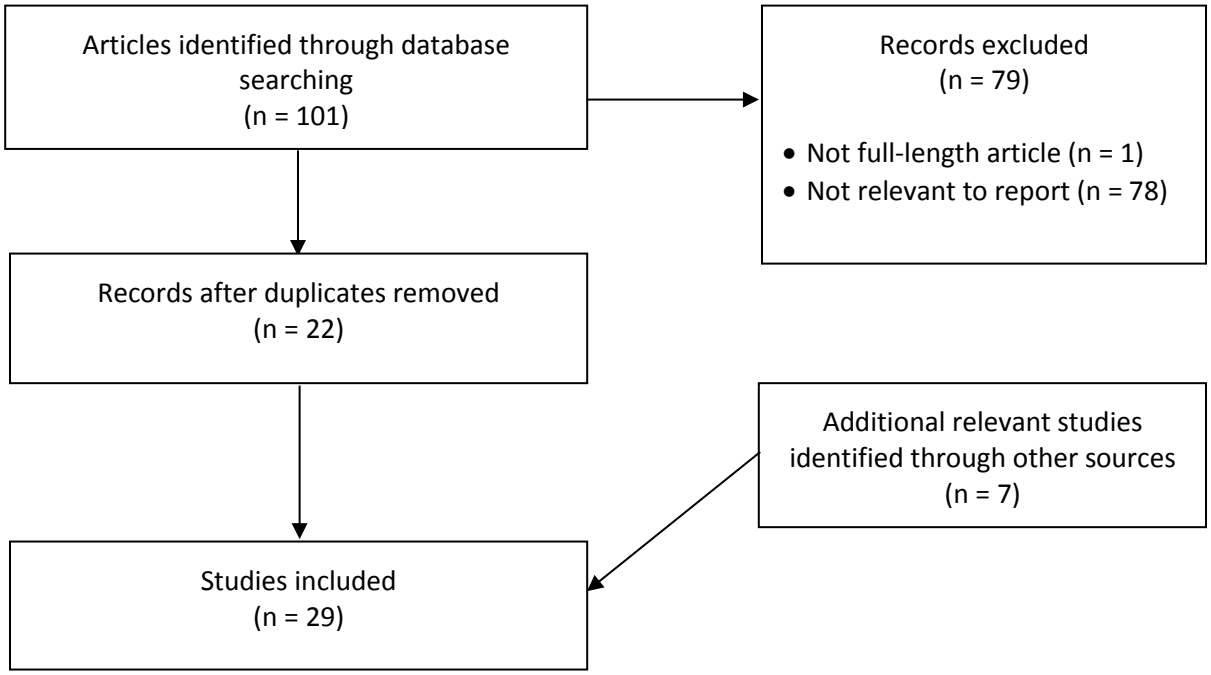
*Information was obtained from publications in peer-reviewed journals and data publicly available on manufacturers websites.

†Device manufacturers: Boston Scientific (formally Guidant Corporation; Boston Scientific Corp, Natick, MA); Medtronic (Medtronic Inc., Minneapolis, Minnesota); Biotronik (Biotronik, Berlin, Germany; and St. Jude Medical device (St Jude Medical Inc., Sylmar, California).

Table S2. Summary of the Strengths and Limitations of D-PA Technology and Extant Research.

Strengths
• CIED accelerometers are built directly into the device and do not require patient participation or additional costs to obtain long-term activity measurements. In contrast, only 12.5% of adults in the US own a wearable fitness tracker (e.g., Fitbit or Actigraph watches, or cellphone app-based tracker)[31] and data from wearable activity trackers are rarely included in medical records. • Device diagnostic information and activity data are collected concurrently and stored for extended periods, making this information uniquely well-suited for examining clinical trends over time, and for longitudinal research. • CIED accelerometers provide continuous objective activity measurement compared to patient-reported activity, which is subjective and less accurate, and traditional activity questionnaires may increase provider and patient burden.[32, 33] • D-PA data are readily available (via device manufacturers) and routinely uploaded into patient electronic-medical records (via device interrogation reports), creating immediate opportunities for use in both research and clinical settings.
Limitations
• CIED accelerometers were developed for the primary purpose of rate-responsive pacing and were not designed to capture data concerning activity type or intensity. • Whether CIED accelerometers are sensitive to detecting D-PA from a broad range of activities (e.g., bicycling, swimming, household chores) is unknown.[8, 17] • Thresholds used to infer meaningful activity from CIED accelerometers differ across manufacturers. • Underrepresentation of women and racial and ethnic minorities limits the generalizability of D-PA findings. Only one published study has examined D-PA in pediatric device patients and activity data in patients with pacemakers is limited. • Heterogeneity in the measurement of D-PA (3 published studies[22-24] used a 'visual estimate' based on activity graphs obtained from clinical reports to measure patient activity) and mortality (deaths reported in clinical trials vs. data obtained from the Social Security Death Index)[8] contribute to inconsistent findings across studies. • Few studies adequately controlled for clinical factors that can influence daily activity in device patients (e.g., episodes of ICD shock and time spent in hospital), or for medical conditions, injuries or symptoms that interfere with ambulatory movement measured by CIED accelerometer (amputation, chronic pain, pulmonary disease, peripheral artery disease, diabetic neuropathy, and osteoporosis).

Figure S1. PRISMA Diagram.



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Measuring Physical Activity With Implanted Cardiac Devices: A Systematic Review

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