Remotely Monitored Cardiac Implantable Electronic Device Data Predict All-Cause and Cardiovascular Unplanned Hospitalization

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BACKGROUND: Unplanned hospitalizations are common in patients with cardiovascular disease. The “Triage Heart Failure Risk Status” (Triage-HFRS) algorithm in patients with cardiac implantable electronic devices uses data from up to 9 device-derived physiological parameters to stratify patients as low/medium/high risk of 30-day heart failure (HF) hospitalization, but its use to predict all-cause hospitalization has not been explored. We examined the association between Triage-HFRS and risk of all-cause, cardiovascular, or HF hospitalization.

METHODS AND RESULTS: A prospective observational study of 435 adults (including patients with and without HF) with a Medtronic Triage-HFRS–enabled cardiac implantable electronic device (cardiac resynchronization therapy device, implantable cardioverter-defibrillator, or pacemaker). Cox proportional hazards models explored association between Triage-HFRS and time to hospitalization; a frailty term at the patient level accounted for repeated measures. A total of 274 of 435 patients (63.0%) transmitted ≥1 high HFRS transmission before or during the study period. The remaining 161 patients never transmitted a high HFRS. A total of 153 (32.9%) patients had ≥1 unplanned hospitalization during the study period, totaling 356 nonelective hospitalizations. A high HFRS conferred a 37.3% sensitivity and an 86.2% specificity for 30-day all-cause hospitalization; and for HF hospitalizations, these numbers were 62.5% and 85.6%, respectively. Compared with a low Triage-HFRS, a high HFRS conferred a 4.2 relative risk of 30-day all-cause hospitalization (8.5% versus 2.0%), a 5.0 relative risk of 30-day cardiovascular hospitalization (3.6% versus 0.7%), and a 7.7 relative risk of 30-day HF hospitalization (2.0% versus 0.3%).

CONCLUSIONS: In patients with cardiac implantable electronic devices, remotely monitored Triage-HFRS data discriminated between patients at high and low risk of all-cause hospitalization (cardiovascular or noncardiovascular) in real time.

Key Words: all-cause hospitalization ■ cardiac-resynchronization therapy ■ cardiovascular hospitalization ■ heart failure ■ implantable cardioverter defibrillators ■ remote monitoring ■ risk prediction
fibrillation, treated ventricular arrhythmias, percentage of biventricular pacing, changes in intrathoracic impedance, and physical activity), continuously and automatically. TriageHF is an integrated diagnostic algorithm that uses a Bayesian Belief Network to combine physiological data derived from compatible Medtronic CIEDs to stratify patients as low-, medium-, or high-risk of HF hospitalization (HFH) in the next 30 days. A patient’s risk status is presented clinically as their maximum HF Risk Status (HFRS) in the preceding 30 days.

The original development and validation of the Triage-HFRS algorithm used pooled data from various historical clinical studies, using data primarily from cardiac resynchronization therapy with defibrillator (CRTD) devices. Since this time, the adoption of remote monitoring ancillary functions has expanded to other devices, such as cardiac resynchronization therapy with pacemaker devices, implantable cardioverters-defibrillators, and pacemakers. This raises the question of clinical utility in a broader population. In addition, recent research has suggested the Triage-HFRS may predict important non-cardiac acute medical events in addition to HFH, an important consideration when designing services for a (generally) older multimorbid population.

Therefore, the aim of this study was to describe the association between the Triage-HFRS and 30-day nonelective hospitalization (all cause, cardiovascular related, and HF related) in a real-world clinical cohort.

METHODS

Data Availability

The study data set will be made available to other researchers for the purpose of reproducing the results on reasonable request to the corresponding author, subject to institutional and ethical committee approvals.

Study Design, Setting, and Participants

This was a prospective observational study of patients with Triage-HFRS–enabled CIEDs (cardiac resynchronization therapy [CRT] device, implantable cardioverter-defibrillator, or pacemaker) in situ, under follow-up at Manchester Heart Centre (England, UK). Patients with at least 1 recorded Triage-HFRS transmission between December 1, 2016, and December 31, 2018, were included. Eligible patients were aged ≥18 years.

Study Outcomes

The primary outcome examined in this study was all-cause nonelective hospitalization. Secondary outcomes were nonelective cardiovascular and nonelective HF.

Ethical Approval

The Health Research Authority’s Confidentiality Advisory Group granted a confidentiality waiver (section 251) in the National Health Service (NHS) Act to link data from electronic health records, cardiac devices, and NHS Digital (as outlined below; 19/Confidentiality Advisory Group/0055). This study complies with the Declaration of Helsinki.
Data Sources and Collection

Demographic data were obtained from integrated electronic hospital care records (Chameleon) and linked primary care data for each patient in the study. Device data were collected via the One Hospital Clinical Service platform, which pulls data from the Medtronic Carelink Network for research and audit purposes. This comprised Triage-HFRS data for the duration of the study, where transmissions had been received. For the duration of the evaluation, the use of the Triage-HFRS was not formally embedded as part of the clinical care pathway, although access to summarized maximum risk status data in the last 30 days was available via the Medtronic Carelink platform.

National Health Service Digital, a centralized service that collates data for all secondary care services provided by the NHS, provided national hospitalization data for the study duration by linking each patient’s NHS number. This ensured hospitalization episodes were recorded for all included patients, regardless of the location of the hospitalization. “Hospitalization” was defined as a nonelective admitted patient care episode. Data corresponding to all hospitalization episodes from January 1, 2017, to December 31, 2018, were obtained. A more detailed outline of NHS Digital data processing is available in Data S1 through S3 and Figures S1 through S3. Secondary Uses Services Healthcare Resource Group (SUSHRG) codes were used to determine if an episode was cardiovascular or HF related. Clinical coding permitting, HF admissions were presented separately to non-HF cardiovascular admissions (more information available at https://digital.nhs.uk/services/secondary-uses-service-sus). All diagnostic codes were independently reviewed by 2 clinicians (authors F.Z.A. and J.K.T.) to ensure correct clinical categorization (Tables S1 through S3).

Statistical Analysis

For descriptive analyses, continuous variables were summarized using the mean (or median for heavily skewed data), with corresponding SDs (interquartile range). Categorical variables were presented as frequencies of occurrence with relative percentages.

Patients were categorized according to the time frame of first recorded high-risk Triage-HFRS. “High at baseline” signified a patient who transmitted a high HFRS before the start of study, or whose first received transmission was “high.” Conversely, patients with no “high” HRFS transmissions before, or during, study duration were categorized as “never high,” and those who transmitted a “high” HFRS for the first time during the study period were categorized as “switchers.” Example profiles for each of these are given in Figure 1.

![Figure 1](image)

**Figure 1.** Example profiles for each of the patient categories: high, switcher, and never high. HFRS indicates Heart Failure Risk Status.
RESULTS

Patients
A total of 435 patients were included in the study, with a total follow-up of 630.1 patient-years. Most patients had a CRT device (77.2%) and New York Heart Association functional class ≥2 (68.0%) at baseline (Table 1). The mean age was 66 years, with 45.7% aged >70 years. Table 1 outlines the demographics of the studied cohort.

In total, 274 of 435 (63.0%) patients transmitted at least 1 high Triage-HFRS transmission; this group was composed of 105 patients categorized as “baseline high” (ie, a high Triage-HFRS either before the study or on first received transmission during study period) and 169 “switchers” (ie, transitioned from a lower-risk status to their first recorded high, during study period) (Figure 1). The remaining 161 patients never transmitted a high Triage-HFRS before, or during, the study (ie, “never high”).

Study Outcomes

Retrospective Analysis: Triage-HFRS Preceding Hospitalization Episodes
There were 356 all-cause hospitalization episodes (128 cardiovascular and 47 HF) throughout the study period (Table 2). In the 30 days before hospitalization, maximum Triage-HFRS was high in 36.85% (131) of cases (of these, 39.1% [n=50] were cardiovascular and 59.6% [n=28] were HFHs). Seven hospitalization episodes were preceded by a 6-month period of stable low HFRS (2%), with no episodes being preceded by a 12-month period of continuous low risk. Further data are available in Data S3.

Prospective Analyses: Triage-HFRS and 30-Day Nonelective Hospitalization

There were 6819 30-day diagnostic evaluation periods (as defined in the Methods section) with complete Triage-HFRS data, from a total of 429 patients. The maximum risk was high for 996 (14.6%), medium for 3535 (51.8%), and low for 2288 (33.6%) 30-day diagnostic evaluation periods. A total of 228 (3.3%) 30-day diagnostic evaluation periods had a corresponding hospitalization in the following 30 days (from the end of each diagnostic evaluation period), of which 89 (39.0%) were cardiovascular-related admissions containing 32 HF-related admissions (Table 3). A high HFRS conferred a 37.3% sensitivity and an 86.2% specificity for 30-day all-cause hospitalization (a nonhigh score offered an NPV of 97.5%). For cardiovascular hospitalizations, sensitivity and specificity were 39.3% and 85.7%, respectively (NPV, 99.1%); and for HFHs, sensitivity and specificity were 62.5% and 85.6%, respectively (NPV, 97.5%).
99.7%). Figure 2 demonstrates the cumulative probability of hospitalization (all cause and cardiovascular) following a first high risk score.

Compared with a diagnostic period with the maximum risk being low, a period evaluated as high risk conferred a 4.2 relative risk (8.5% versus 2.0%) of a 30-day all-cause hospitalization, a 5.0 relative risk (3.6% versus 0.7%) of a 30-day cardiovascular hospitalization, and a 7.7 relative risk (2.0% versus 0.3%) of a 30-day HFH (Table 3). Figure 3 illustrates the Kaplan-Meier cumulative probability of hospitalization by type, indicating clear differences between the maximum recorded risk within 30 days being high compared with medium or low. Demographics of patients who experienced hospitalizations are provided in Table S10.

Compared with low HFRS evaluations, a high HFRS evaluation was associated with significantly increased risk of subsequent 30-day all-cause and cardiovascular hospitalization. We observed a hazard ratio (HR) of 2.9 (95% CI, 1.88–4.40; P<0.001) for the high-HFRS evaluations compared with low-HFRS evaluations for subsequent 30-day all-cause hospitalization events, and an HR of 4.1 (95% CI, 2.08–8.01; P<0.001) for cardiovascular hospitalization when fitting the frailty models to the data (Table 4). The latter remained significant when adjusting the model for nonproportional hazards (Table S11) to a HR of 2.4 (95% CI, 1.65–3.51; P<0.001). In addition, having a non-CRT device was associated with a decreased hazard of a patient having an all-cause hospitalization (permanent pacemaker: HR, 0.40 [95% CI, 0.18–0.94]; P=0.03; implantable cardioverter-defibrillator: HR, 0.31 [95% CI, 0.12–0.81]; P=0.02) compared with those with a CRTD device (Table 4).

### Cost Analysis

The cost of all-cause hospitalization for high-, medium-, or low-risk status events was £245924, £209337, and £93604, respectively (Table S12). Over 38% of these total costs were attributed to cardiovascular hospitalizations within each risk group (high, 42.4%; medium, 38.6%; low, 41.6%). Across all-cause hospitalization, cardiovascular hospitalization, and HFH, the cost of

### Table 1. Baseline Patient Demographics

| Demographic | Total | Baseline high | Switcher | Never high | P value |
|-------------|-------|---------------|----------|------------|---------|
| Patients, n | 435   | 105           | 169      | 161        |         |
| Age, mean (SD), y | 66.0 (15.5) | 68.3 (14.7) | 67.3 (15.5) | 63.2 (15.6) | 0.011   |
| Men | 276 (63.4) | 62 (59) | 112 (66.3) | 102 (63.4) | 0.482   |
| Device type | | | | | 0.161 |
| CRTD | 166 (38.2) | 36 (34.3) | 67 (39.6) | 63 (39.1) |         |
| CRTP | 170 (39.0) | 46 (43.8) | 70 (41.4) | 54 (33.5) |         |
| ICD | 36 (8.3) | 5 (4.8) | 11 (6.9) | 20 (12.4) |         |
| PPM | 63 (14.5) | 18 (17.1) | 21 (12.4) | 24 (14.9) |         |
| NYHA class (missing data n=22) | | | | | 0.056 |
| No heart failure | 62 (14.3) | 13 (12.4) | 19 (11.2) | 30 (18.6) |         |
| 1 | 55 (12.6) | 9 (8.6) | 17 (10.1) | 29 (18) |         |
| 2 | 151 (34.7) | 39 (37.1) | 61 (36.1) | 51 (31.7) |         |
| ≥3 | 145 (33.3) | 37 (35.2) | 63 (37.3) | 45 (28) |         |
| LVEF <35 (missing data n=6), % | 241 (56.1) | 61 (58.1) | 102 (60.4) | 78 (48.4) | 0.071   |
| Atrial fibrillation/flutter (missing data n=3) | 188 (43.2) | 52 (49.5) | 78 (46.2) | 58 (36.0) | 0.070   |
| Diabetes (missing data n=18) | 103 (23.7) | 27 (25.7) | 45 (26.6) | 31 (19.3) | 0.264   |
| COPD (missing data n=17) | 54 (12.4) | 15 (14.3) | 21 (12.4) | 18 (11.2) | 0.807   |
| CKD stage ≥3 (missing data n=4) | 134 (30.8) | 35 (33.3) | 53 (31.4) | 46 (28.6) | 0.654   |
| At least 1 comorbidity (missing data n=10)* | 388 (89.2) | 98 (83.3) | 156 (92.3) | 134 (83.2) | <0.001 |

Data are indicated as number (percentage), unless otherwise stated. ACE-I indicates angiotensin-converting enzyme inhibitor; ARB, angiotensin receptor blocker; ARNI, angiotensin receptor and neprolysin inhibitor; CKD, chronic kidney disease; COPD, chronic obstructive pulmonary disease; CRTD, cardiac resynchronization therapy with defibrillator; CRTP, cardiac resynchronization therapy with pacemaker; ICD, implantable cardioverter-defibrillator; LVEF, left ventricular ejection fraction; MRA, mineralocorticoid receptor antagonist; NYHA, New York Heart Association; and PPM, permanent pacemaker.

*Including heart failure, atrial fibrillation/flutter, diabetes, COPD, and CKD stage ≥3.
hospitalization was markedly higher for high Triage-HFRS status events compared with medium- and low-risk events (Tables S12 and S13). Although just 14.6% of the diagnostic episodes were evaluated as being high, they contributed to 44.8% of the overall costs for all-cause hospitalization and 69.6% of the overall costs of the HFHs, highlighting the disproportionate impact on cost associated with a high Triage-HFRS (Figure 4). Furthermore, the cost of an all-cause hospitalization corresponding to a high Triage-HFRS was on average >£1000 more than the average cost of an all-cause hospitalization corresponding to a low Triage-HFRS (Table S12). The average cost for all-cause hospitalizations was >50% higher in those who had at least 1 day evaluated as a high HFRS compared with those who were low for the entire 30 days before the hospitalization (£3616.33 versus £2340.10).

**DISCUSSION**

This is the first prospective real-world study to report that remotely monitored risk data from cardiac devices, originally developed to identify patients at increased risk of HFH, can also be used to predict all-cause and cardiovascular unplanned hospitalization. The key findings were as follows: (1) experiencing any high-risk episode was associated with significantly increased risk of all-cause and cardiovascular hospitalization and (2) a nonhigh Triage-HFRS conferred a >97% NPV of all-cause and cardiovascular hospitalization. Therefore, the Triage-HFRS is a useful tool to risk stratify patients according to their risk of 30-day healthcare use.

### Triage-HFRS and All-Cause Hospitalization

In contrast to previous studies, the current analysis examined noncardiovascular hospitalizations to understand the utility of Triage-HFRS to be used more broadly. A high Triage-HFRS 30-day maximum risk was associated with a 4.2 relative risk and a 2.9-fold increased hazard of 30-day all-cause hospitalization. A total of 1 in 6 patients had an unplanned admission following their first high, with most occurring within 3 months. The retrospective analysis provides additional insights; 1 in 3 patients who experienced an unplanned all-cause hospitalization had transmitted a high Triage-HFRS in the preceding 30 days. The leading diagnoses for these admissions included respiratory infections and sepsis. Given some of the nonspecific components of the Triage-HFRS algorithm (eg, heart rate and physical activity), it is not surprising that a high Triage-HFRS preceded noncardiovascular admissions. In addition, thoracic impedance measures are known to be affected by clinical states without concurrent ventricular dysfunction. This highlights the
need for a high HFRS to be interpreted clinically, particularly in patients with significant comorbidities.

**Triage-HFRS and Cardiovascular Hospitalization**

The wider utility of Triage-HFRS to predict and identify a broader range of cardiovascular causes of hospitalization beyond HF alone is of interest to the general cardiology community. To date, only one study has previously examined the association between Triage-HFRS and cardiovascular hospitalizations; a post hoc analysis of the MORE-CARE (The Monitoring Resynchronization Devices and Cardiac Patients) Randomized Controlled Trial (patients enrolled between 2009–2014), originally designed to examine the efficacy of remote monitoring in patients with CRTD, reported that a high-risk status was associated with a 4.5 relative risk of 30-day cardiovascular hospitalization. In the current study, when all device types are considered, we report that the relative risk of a 30-day cardiovascular hospitalization was 5.0 and an associated HR of 2.4, where common non-HF cardiovascular hospitalizations included arrhythmias, chest pain, myocardial infarction, and angina. The retrospective analysis provides a different perspective; 1 in 3 patients with an unplanned cardiovascular hospitalization and 60% of those with HFH transmitted a high Triage-HFRS in the preceding 30 days.

When considering longer-term risk of hospitalization, most cardiovascular hospitalizations (over two thirds) were preceded by a high TriageHF risk status in the 12 months before admission. Of those who experienced an HFH, 87.5% had a CRT device, and 3 in 4 HFHs had a high-risk status recorded within the previous 12 months.

**Triage-HFRS, Device Type, and HFH**

Previous evaluations of Triage-HFRS have, for the most part, examined utility to identify patients with CRTD at

| 30-d Diagnostic evaluation period maximum Triage-HFRS | Total diagnostic evaluation periods | 30-d Hospitalizations |
|-------------------------------------------------------|-----------------------------------|------------------------|
| Low                                                   | 2288 (33.6)                       | 46 (2.0)               |
| Medium                                                | 3535 (51.8)                       | 97 (2.7)               |
| High                                                  | 996 (14.6)                        | 85 (8.5)               |
| Total                                                 | 6819 (100)                        | 228 (3.3)              |

Data are given as number (percentage). Triage-HFRS indicates Triage Heart Failure Risk Status.

![Figure 2](image_url)

**Figure 2.** Kaplan-Meier cumulative incidence curves of a subsequent all-cause and cardiovascular hospitalization episode following the start of the first date a patient was recorded as being in high risk for the patients who experienced their first high Heart Failure Risk Status during the study (ie, switchers).

All-cause hospitalizations occurred more frequently within the first 180 days, but cardiovascular events occurred linearly with time.
increased risk of HFH. Using pooled data from historical studies undertaken between 2004 and 2008,10–14 the original validation of Triage-HFRS reported that a high-risk status was associated with a 10-fold increase in risk of 30-day HFH.3

We present results for an unselected, real-world cohort across the entire spectrum of Triage-HFRS-compatible devices. This is important clinically as it more accurately represents the population being monitored, encompassing a broader population of patients that also includes those without an HF diagnosis and patients with cardiac resynchronization therapy with pacemaker and permanent pacemaker devices. It was anticipated this would confer a lower hospitalization rate compared with previous Triage-HFRS evaluations; however, in fact, we found that risk of 30-day HFH was similar.15,16 We report that having a non-CRT device was associated with a decreased hazard of a patient having an all-cause hospitalization compared with those with a CRTD device, with fewest hospitalizations observed in patients with non-CRT devices. However, although >75% of the patients in our sample had CRT devices, the results found that HF and device type were not significant in relation to cardiovascular hospitalization (Table S14 compares New York Heart Association class across device types). This is reassuring in terms of the utility of HF monitoring in non-CRT devices. However, further analyses in populations with higher proportions of non-CRT devices could be warranted.

We found that when all devices are considered, experiencing at least 1 day in a high-risk status resulted in a relative risk of 7.8 for a 30-day HFH. In the current analysis, only 1 in 8 unplanned HFHs occurred in patients without CRT. Furthermore, we found that having a brady pacemaker (non-CRT) was associated with a decreased hazard of a

| Variable          | All-cause hospitalizations within 30d | Cardiovascular hospitalizations within 30d |
|-------------------|--------------------------------------|------------------------------------------|
|                   | Hazard ratio | 95% CI   | P value | Hazard ratio | 95% CI   | P value |
| Medium (vs low)   | 1.126     | 0.764–1.658 | 0.55     | 1.371     | 0.735–2.561 | 0.32     |
| High (vs low)     | 2.874*    | 1.878–4.399 | <0.001* | 4.080*    | 2.077–8.012 | <0.001* |
| No heart failure  | 0.961     | 0.423–2.180 | 0.92     | 0.975     | 0.293–3.247 | 0.97     |
| Age               | 1.015*    | 1.000–1.031 | 0.05*    | 1.017     | 0.993–1.041 | 0.17     |
| CRTP vs CRTD      | 0.668     | 0.428–1.042 | 0.08     | 0.559*    | 0.285–1.097 | 0.09     |
| PPM vs CRTD       | 0.405†    | 0.175–0.937 | 0.03*    | 0.549‡    | 0.167–1.806 | 0.32     |
| ICD vs CRTD       | 0.306*    | 0.116–0.807 | 0.02*    | 0.268     | 0.063–1.146 | 0.08     |
| CKD stage ≥3      | 1.282     | 0.832–1.981 | 0.26     | 1.245†    | 0.643–2.412 | 0.52     |

CKD indicates chronic kidney disease; CRTD, cardiac resynchronization therapy with defibrillator; CRTP, cardiac resynchronization therapy with pacemaker; ICD, implantable cardioverter-defibrillator; and PPM, permanent pacemaker.

*Denotes that the comorbidities assessed include one or more of these conditions.

†Indicates a time-varying coefficient where nonproportional hazards were observed. Further analyses performed to stratify details are provided in Table S11.
decreased hazard of all-cause hospitalization. These findings suggest that remote monitoring of HF risk status is likely to be most advantageous in populations with CRT, in those in whom HF and poor functional status are more prevalent, and adds little value in patients with brady pacemakers.

Cost Perspectives
The financial cost of hospitalizations associated with a high Triage-HFRS status was significantly higher compared with those associated with a medium- or low-risk status. For the prospective analyses, even though only 14.6% of the diagnostic episodes were evaluated as being high, they contributed to 69.6% of the overall costs of the HFHs, highlighting that although high-risk episodes constituted only a small proportion of the overall follow-up, hospitalizations associated with these episodes had a disproportionate impact on cost. Furthermore, the all-cause hospitalizations corresponding to a high-risk evaluation had an average increased cost of >£1000 compared with the low-risk evaluations, largely driven by noncardiovascular hospitalizations. This indicates that there is a potential cost-benefit of targeting patients with a high Triage-HFRS to prevent both cardiovascular and noncardiovascular hospitalizations.

Clinical Perspectives
Identifying high-risk patients with HF is an important aspect of clinical care. Several multivariable risk scores for the prediction of outcomes in patients with HF have been developed. However, for the most part, these focus on predicting risk of all-cause mortality rather than hospitalization. Stratifying risk of HFH in an ambulatory population with chronic HF remains an area of primary research. Another important limitation of traditional risk models is that they become outdated if there is a change in clinical circumstance (e.g., the patient gets older or there is a change in medications or blood pressure). Device-based risk prediction models take a different approach to traditional risk models and are aligned to “risk” being a dynamic process that is continuously changing. Device-derived measurements are continuously monitored and automatically updated on a daily basis, enabling dynamic real-time assessment of risk of both hospitalization and mortality.

The TriageHF alert-based monitoring system has been available for clinical use in the United Kingdom since 2016; however, formal monitoring has been limited to a small number of enthusiastic centers. This study highlights the utility of the Triage-HFRS to risk stratify patients according to risk of 30-day hospitalization. Given the limited resources of HF community teams, using the Triage-HFRS to guide the prioritization of specialist care to patients at high risk of HF decompensation could be both clinically advantageous and cost saving. The best way to implement this and assess impact on clinical outcomes is an area of ongoing research (TriageHF Plus ClinicalTrials.gov Identifier: NCT04177199). In addition, an NPV of 99.7% for HFH may justify use as a screening tool to identify stable patients for whom monitoring frequency can be deescalated.

Limitations
Although hospital episode data were available from January 1, 2017, to December 31, 2018, the risk score data availability depends on the implant date of a Triage-HFRS-compatible device and contact with the home monitoring console. Consequently, the risk score may not cover the study period for all patients. Overall, the average follow-up per patient for the transmission data was 521.4 days. A small proportion of the transmission data was missing (1.9%), with most patients having no missing transmission data (n=396 [92.3%]). Of those who did have missing transmission data, the average number of days that a patient was missing transmission data was 10.1 days. There are some periods of missing HFRS data before hospitalization. This could correspond to an
incorrect classification when evaluating the maximum risk before the event. For example, 19 of the all-cause nonelective admissions that only transmitted low-risk statuses had at least 1 day without a risk status and could have experienced a higher risk on one of these days. Similarly, we did not have information on some potentially important baseline demographic data, such as race and ethnicity.

Admitted patient care hospitalization diagnoses are based on SUSHRG codes, which differ slightly from International Classification of Diseases (ICD-10) codes. Although most codes led to consistent classification into cardiovascular HF, cardiovascular non-HF, and noncardiovascular, there were 11 of 356 (3.1%) admitted patient care episodes that were incongruent (Table S15). This could be in part because only one primary SUSHRG code per admission is recorded; therefore, concurrent diagnoses may be missed. Once hospitalized, patients often receive treatment for >1 acute medical problem. However, as only one SUSHRG code is assigned per admission, the true cost of care may be underestimated, particularly in those patients who receive treatment for multiple problems and those who develop hospital-acquired complications. Furthermore, the clinical coding for accident and emergency department admissions did not distinguish between HF and non-HF cardiovascular events. See Tables S1 through S3, S9, and S15 for more detail on SUSHRG codes.

In this analysis, it was not possible to evaluate the association between the HFRS and HFH because of the small number of episodes. Furthermore, the cohort contained relatively small numbers of patients with non-CRTS (implantable cardiovers-defibrillators in particular) because of the demographic of the population who had compatible devices. This is attributable to the way that TriageHF technology was available (according to device type) at inception. A larger study would be required to more accurately estimate the associations within this subpopulation. Finally, as is commonplace in clinical practice, a service improvement project was underway during the course of the current evaluation, whereby the Triage-HFRS data were available for review by the cardiac care team via the Carelink platform.

Therefore, although the current study did not consider the impact of any downstream human interaction out with standard care, Triage-HFRS data for 1.9% of episodes (127/6819 episodes) were reviewed by the cardiac care team. Because of the small numbers, this is unlikely to have had an impact on the results of the current evaluation.

CONCLUSIONS

Remotely monitored, risk-based CIED-derived data identify patients at higher risk of 30-day all-cause, cardiovascular, and HF hospitalization. Future research should focus on using the Triage-HFRS as a remote clinical management tool to facilitate rapid medical intervention, either remote or in the community, potentially avoiding need for hospitalization.
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SUPPLEMENTAL MATERIAL
Data S1. NHS Digital data processing

For the admitted patient care episodes, we had only 1 episode with a missing length of stay after cleaning. However, this event occurred after the final transmitted HFRS, hence its length of stay (LoS) would not affect the validation. For the episodes which overlapped with other episodes, the earliest episode with the longest length of stay was chosen. Of those that were excluded, only 2 cardiovascular episodes were excluded in favour of a non-cardiovascular episode with a longer LoS admitted on the same date, 10 were excluded for occurring within a previous episode but none of these affected the episode type (cardiovascular vs non-cardiovascular). There were 570 A&E admissions recorded within the HFRS follow up (+30 days) between 1 Jan 2017 and 31 Dec 2018. After data cleaning and removal of duplicate entries, there were a total of 554 A&E admissions. The exclusion diagrams are shown in Figure S1.

Of the 554 ED admissions, 314 were matched to an APC episode with the same date of admission (n=219) or admission the day after that of the A&E episode (n=95). Of these matched admissions, 181 were recorded as non-cardiovascular for both A&E and APC, 39 were non-cardiovascular A&E admissions but had a cardiovascular APC, 28 were a cardiovascular A&E but non-cardiovascular APC and 66 were cardiovascular for both the A&E admission and APC episode. Seven of the A&E admissions were linked to ‘elective’ or ‘other’ admission types.
Data S2. Evaluation Period Generation

For each patient,

1. Initiate the start date as the first recorded HFRS transmission within the follow up of that patient.

2. For the given start date, define a (patient-level) 30-day evaluation period to be 30 consecutive days from the start date.

3. Determine whether:

   a. the last recorded HFRS occurs after the end of the 30-day evaluation period: if not, there is not enough HFRS data for this period, move on to the next patient and restart procedure.

   b. there is HFRS data for all 30 days: if not, determine where the data is missing and reset the start date as the first date with HFRS data after the break

   c. there are no overlaps of HFRS captured: if there are overlaps, reset the start date as the first date after all overlapping periods have ended

   d. there were no non-elective hospitalisations: if there was a non-elective hospitalisation, reset the start date as the day after discharge
e. If none of (a)-(d) occurred, determine this as a suitable 30-day diagnostic evaluation period. Then reset the start date as the day following the last day of the 30-day diagnostic evaluation period. For the remaining periods, the maximum risk over the 30 days was recorded and the outcome was the time to hospitalisation within the next 30 days.

4. Repeat steps 2 and 3 using the new start date defined in step 3.
Data S3. Retrospective analyses: Maximum Triage-HFRS prior to non-elective hospitalisation

Out of the 435 patients, 153 patients (35.2%) had a non-elective all-cause hospitalisation at least once during the study period, with 76 of these patients having a cardiovascular non-elective admission. In total, there were 356 all-cause non-elective hospitalisations during the 2-year study period (median [min-max]: 0 [0–11] hospitalisations per patient); this corresponds to a rate of 0.565 all-cause non-elective hospitalisations per patient-year. Over one third (128/356) of these hospitalisations were cardiovascular related admissions, with HF identified as a primary diagnosis in 36.7% (47/128) of these. Common, non-HF cardiovascular admissions included; arrhythmia (n=21), chest pain (n=12), other acquired cardiac conditions (n=10), syncope/collapse (n=9), actual or suspected MI (n=6) and angina (n=6). Common, non-cardiovascular admissions included; respiratory infection or pneumonia (n=27), gastrointestinal tract disorder (n=18) and sepsis (n=10).

Of the 153 patients with at least one hospitalisation during the study period, 130 (85.0%) had a CRT device (CRT-P, 64 (41.8%); CRT-D, 66 (43.1%)), 9 (5.9%) an ICD, and 14 (9.2%) a PPM. For those who experienced a HF hospitalisation (n=31), 90.3% had a CRT device.

The majority (234/356; 65.7%) of all-cause hospitalisations took place within 1 year of a high Triage-HFRS episode and 36.8% had a high-risk status within the 30 days prior to the hospitalisation. Isolating cardiovascular hospitalisations, 85/128 (66.4%) had a high-risk status in the
preceding 12 months, 76/128 (59.4%) within the previous 6-months, and 50/128 (39.2%) in the preceding 30-days, while 34/47 (72.3%) HF hospitalisations transmitted a high HFRS status within the previous 6-months. The majority of patients with a non-elective HF hospitalisation (59.6%), transmitted a high Triage-HFRS in the preceding 30-days (Table 2).

Of the 169 'switchers', 29 (17.2%) experienced a subsequent cardiovascular hospitalisation during the study period. For these patients, the median time from the start of their first recorded high-risk episode to the cardiovascular hospitalisation was 92 days (IQR: 39 - 211). The proportion of these admissions which occurred within 30 days was modest (5/29; 17.2%) but 48.3% occurred within 3 months, 69.0% (14/29) occurred within 6 months, and nearly all occurred within 12 months (20/29; 93.1%). The Kaplan-Meier cumulative incidence curves from a patient’s first high episode to subsequent hospitalisation within the study period are shown in Figure 2. The median duration of the first high episode was 6 days (IQR: 3 – 12 days) and the length of time spent in this first high was not associated with a change in hazard for non-elective cardiovascular hospitalisation (p=0.949).
| SUSHRG code | HRG Name |
|-------------|----------|
| EA03Z       | Pace 1: Single Chamber or Implantable Diagnostic Device |
| EA05Z       | Pace 2: Dual Chamber |
| EA07Z       | Pace 3: Biventricular and all Congenital Pacemaker Procedures; Resynchronisation Therapy |
| EA09Z       | Percutaneous Interventions: Percutaneous Transluminal ASD, VSD or PFO Closure and Valve Insertion |
| EA11Z       | Percutaneous Interventions: Other including Septostomy, Embolisations, Non-Coronary Stents and Energy Moderated Perforation |
| EA12Z       | Implantation of Cardioverter; Defibrillator only |
| EA14Z       | Coronary Artery Bypass Graft (First Time) |
| EA17Z       | Single Cardiac Valve Procedures |
| EA19Z       | Single Cardiac Valve Procedures with Percutaneous Coronary Intervention, Pacing, EP or RFA |
| EA24Z       | Complex Congenital Surgery |
| EA29Z       | Percutaneous Complex Ablation, including for Atrial Fibrillation or Ventricular Tachycardia |
| EA31Z       | Percutaneous Coronary Intervention, 0 to 2 Stents |
| EA36A       | Catheter, 19 years and over |
| EA39Z       | Pacemaker Procedure without Generator Implant, including Re-siting and Removal of Cardiac Pacemaker System |
| EA44Z       | Minor Cardiac Procedures |
| EA45Z       | Complex Echocardiogram, including Congenital, Transoesophageal and Fetal Echocardiography |
| Code  | Description                                                                 |
|-------|-----------------------------------------------------------------------------|
| EA49Z | Percutaneous Coronary Interventions with 3 or more Stents, Rotablation, IVUS or Pressure Wire |
| EA51Z | Coronary Artery Bypass Graft, with Valve Replacement or Repair              |
| EA52Z | Repair or Replacement of more than one Heart Valve                          |
| EA53Z | Transcatheter Aortic Valve Implantation (TAVI)                              |
| EA54Z | Percutaneous Standard Ablation                                              |
| EA56Z | Implantation of Cardiac Resynchronization Therapy Defibrillator (CRT-D)     |
| EB01Z | Non-Interventional Acquired Cardiac Conditions                              |
| EB02A | Endocarditis with CC Score 10+                                              |
| EB03A | Heart Failure or Shock, with CC Score 14+                                   |
| EB03B | Heart Failure or Shock, with CC Score 11-13                                 |
| EB03C | Heart Failure or Shock, with CC Score 8-10                                  |
| EB03D | Heart Failure or Shock, with CC Score 4-7                                   |
| EB03E | Heart Failure or Shock, with CC Score 0-3                                   |
| EB03H | Heart Failure or Shock, without CC                                           |
| EB05C | Cardiac Arrest with CC Score 0-4                                            |
| EB06B | Cardiac Valve Disorders with CC Score 9-12                                  |
| EB06D | Cardiac Valve Disorders with CC Score 0-4                                   |
| EB06Z | Cardiac Valve Disorders                                                     |
| EB07A | Arrhythmia or Conduction Disorders, with CC Score 13+                       |
| EB07B | Arrhythmia or Conduction Disorders, with CC Score 10-12                     |
| EB07C | Arrhythmia or Conduction Disorders, with CC Score 7-9                       |
| EB07D | Arrhythmia or Conduction Disorders, with CC Score 4-6                       |
| EB07E | Arrhythmia or Conduction Disorders, with CC Score 0-3                       |
| EB07H | Arrhythmia or Conduction Disorders, without CC                              |
| EB07I | Arrhythmia or Conduction Disorders, without CC                              |
| Code  | Description                                                                 |
|-------|-----------------------------------------------------------------------------|
| EB08A | Syncope or Collapse, with CC Score 13+                                      |
| EB08B | Syncope or Collapse, with CC Score 10-12                                    |
| EB08C | Syncope or Collapse, with CC Score 7-9                                       |
| EB08D | Syncope or Collapse, with CC Score 4-6                                       |
| EB08E | Syncope or Collapse, with CC Score 0-3                                       |
| EB08H | Syncope or Collapse, with CC                                                 |
| EB08I | Syncope or Collapse, without CC                                              |
| EB09A | Non-Interventional Congenital Cardiac Conditions with CC Score 3+            |
| EB10A | Actual or Suspected Myocardial Infarction, with CC Score 13+                 |
| EB10B | Actual or Suspected Myocardial Infarction, with CC Score 10-12               |
| EB10C | Actual or Suspected Myocardial Infarction, with CC Score 7-9                 |
| EB10D | Actual or Suspected Myocardial Infarction, with CC Score 4-6                 |
| EB10Z | Actual or Suspected Myocardial Infarction                                    |
| EB12A | Unspecified Chest Pain with CC Score 11+                                    |
| EB12B | Unspecified Chest Pain with CC Score 5-10                                    |
| EB12C | Unspecified Chest Pain with CC Score 0-4                                     |
| EB13A | Angina with CC Score 12+                                                     |
| EB13B | Angina with CC Score 8-11                                                    |
| EB13C | Angina with CC Score 4-7                                                     |
| EB14A | Other Acquired Cardiac Conditions with CC Score 13+                          |
| EB14B | Other Acquired Cardiac Conditions with CC Score 9-12                         |
| EB14C | Other Acquired Cardiac Conditions with CC Score 6-8                          |
| EB14D | Other Acquired Cardiac Conditions with CC Score 3-5                          |
| EB14E | Other Acquired Cardiac Conditions with CC Score 0-2                          |
| EC10B | Very Complex Procedures for Congenital Heart Disease with CC Score 7-14     |
| EC10C | Very Complex Procedures for Congenital Heart Disease with CC Score 0-6      |
| EC11C | Complex Procedures for Congenital Heart Disease with CC Score 0-6            |
| Code  | Description                                                                 |
|-------|-----------------------------------------------------------------------------|
| EC12B | Very Major Procedures for Congenital Heart Disease with CC Score 4-8        |
| EC13B | Major Procedures for Congenital Heart Disease with CC Score 4-8             |
| EC15A | Minor Procedures for Congenital Heart Disease with CC Score 4+              |
| EC15B | Minor Procedures for Congenital Heart Disease with CC Score 0-3             |
| EC20A | Diagnostic Percutaneous Intervention for Congenital Heart Disease with CC Score 4+ |
| EC20B | Diagnostic Percutaneous Intervention for Congenital Heart Disease with CC Score 0-3 |
| ED22B | Complex, Coronary Artery Bypass Graft with Single Heart Valve Replacement or Repair, with CC Score 0-3 |
| ED24B | Complex, Single Heart Valve Replacement or Repair, with CC Score 6-10       |
| ED24C | Complex, Single Heart Valve Replacement or Repair, with CC Score 0-5        |
| ED25A | Standard, Single Heart Valve Replacement or Repair, with CC Score 11+       |
| ED25B | Standard, Single Heart Valve Replacement or Repair, with CC Score 6-10     |
| ED26A | Complex Coronary Artery Bypass Graft with CC Score 10+                      |
| ED26B | Complex Coronary Artery Bypass Graft with CC Score 5-9                      |
| ED27C | Major Coronary Artery Bypass Graft with CC Score 0-4                       |
| EY01A | Implantation of Cardioverter Defibrillator with Cardiac Resynchronisation Therapy, with CC Score 9+ |
| EY01B | Implantation of Cardioverter Defibrillator with Cardiac Resynchronisation Therapy, with CC Score 0-8 |
| EY02A | Implantation of Cardioverter Defibrillator with CC Score 9+                |
| EY02B | Implantation of Cardioverter Defibrillator with CC Score 0-8               |
| EY03Z | Implantation of Biventricular Pacemaker with Other Percutaneous Intervention |
| EY04A | Implantation of Biventricular Pacemaker with CC Score 6+                   |
| EY04B | Implantation of Biventricular Pacemaker with CC Score 0-5                  |
| EY05A | Implantation of Dual-Chamber Pacemaker with Other Percutaneous Intervention, with CC Score 6+ |
| Code   | Description                                                                 |
|--------|-----------------------------------------------------------------------------|
| EY05B  | Implantation of Dual-Chamber Pacemaker with Other Percutaneous Intervention, with CC Score 0-5 |
| EY06A  | Implantation of Dual-Chamber Pacemaker with CC Score 12+                     |
| EY06B  | Implantation of Dual-Chamber Pacemaker with CC Score 9-11                    |
| EY06D  | Implantation of Dual-Chamber Pacemaker with CC Score 3-5                     |
| EY06E  | Implantation of Dual-Chamber Pacemaker with CC Score 0-2                     |
| EY07A  | Implantation of Single-Chamber Pacemaker with Other Percutaneous Intervention, with CC Score 6+ |
| EY07B  | Implantation of Single-Chamber Pacemaker with Other Percutaneous Intervention, with CC Score 0-5 |
| EY08A  | Implantation of Single-Chamber Pacemaker with CC Score 12+                   |
| EY08B  | Implantation of Single-Chamber Pacemaker with CC Score 9-11                  |
| EY08C  | Implantation of Single-Chamber Pacemaker with CC Score 6-8                   |
| EY08D  | Implantation of Single-Chamber Pacemaker with CC Score 3-5                   |
| EY08E  | Implantation of Single-Chamber Pacemaker with CC Score 0-2                   |
| EY09B  | Removal of Cardiac Pacemaker or Cardioverter Defibrillator, with CC Score 0-5 |
| EY10A  | Attention to Cardiac Pacemaker or Cardioverter Defibrillator, with CC Score 6+ |
| EY10B  | Attention to Cardiac Pacemaker or Cardioverter Defibrillator, with CC Score 0-5 |
| EY11Z  | Testing of Cardiac Pacemaker or Cardioverter Defibrillator                   |
| EY13Z  | Removal of Electrocardiography Loop Recorder                                 |
| EY20A  | Transcatheter Aortic Valve Implantation (TAVI) using Other Approach, with CC Score 8+ |
| EY20B  | Transcatheter Aortic Valve Implantation (TAVI) using Other Approach, with CC Score 0-7 |
| EY21A  | Transcatheter Aortic Valve Implantation (TAVI) using Transfemoral Approach, with CC Score 8+ |
| Code  | Description                                                            |
|-------|------------------------------------------------------------------------|
| EY22A | Complex Other Percutaneous Transluminal Repair of Acquired Defect of Heart with CC Score 10+ |
| EY22B | Complex Other Percutaneous Transluminal Repair of Acquired Defect of Heart with CC Score 5-9 |
| EY30A | Complex Percutaneous Transluminal Ablation of Heart with CC Score 3+   |
| EY30B | Complex Percutaneous Transluminal Ablation of Heart with CC Score 0-2 |
| EY31A | Standard Percutaneous Transluminal Ablation of Heart with CC Score 3+ |
| EY31B | Standard Percutaneous Transluminal Ablation of Heart with CC Score 0-2 |
| EY32A | Percutaneous Diagnostic Electrophysiology Studies with CC Score 2+    |
| EY40C | Complex Percutaneous Transluminal Coronary Angioplasty with CC Score 4-7 |
| EY41A | Standard Percutaneous Transluminal Coronary Angioplasty with CC Score 12+ |
| EY41B | Standard Percutaneous Transluminal Coronary Angioplasty with CC Score 8-11 |
| EY41C | Standard Percutaneous Transluminal Coronary Angioplasty with CC Score 4-7 |
| EY41D | Standard Percutaneous Transluminal Coronary Angioplasty with CC Score 0-3 |
| EY42A | Complex Cardiac Catheterisation with CC Score 7+                       |
| EY43A | Standard Cardiac Catheterisation with CC Score 10-12                   |
| EY43B | Standard Cardiac Catheterisation with CC Score 7-9                     |
| EY43C | Standard Cardiac Catheterisation with CC Score 4-6                     |
| EY43D | Standard Cardiac Catheterisation with CC Score 2-3                     |
| EY43E | Standard Cardiac Catheterisation with CC Score 0-1                     |
| EY43F | Standard Cardiac Catheterisation with CC Score 0-1                     |
| EY50Z | Complex Echocardiogram                                                |
| EY51Z | Electrocardiogram Monitoring or Stress Testing                        |

CC = comorbidities score
|                          | Max risk recorded in previous 30 days | Max risk recorded in previous 6 months | Max risk recorded in previous 12 months |
|--------------------------|---------------------------------------|----------------------------------------|----------------------------------------|
|                          | Low        | Med     | High | No txs received | Low     | Med     | High | No txs received | Low     | Med     | High | No txs received | Total |
| All-cause, n (%)         | 150 (24.9%) | 261 (43.3%) | 184 (30.5%) | 8 (1.3%) | 17 (2.8%) | 277 (45.9%) | 307 (50.9%) | 2 (0.3%) | 234 (38.8%) | 367 (60.9%) | 0 (0.0%) | 603 |
| CV, n (%)                | 31 (16.9%) | 81 (44.3%) | 67 (36.6%) | 4 (2.2%) | 4 (2.2%) | 70 (38.3%) | 108 (59.0%) | 1 (0.5%) | 61 (33.3%) | 121 (66.1%) | 0 (0.0%) | 183 |
| HF, n (%)                | 5 (10.6%) | 12 (25.5%) | 28 (59.6%) | 2 (4.3%) | 0 (0.0%) | 12 (25.5%) | 34 (72.3%) | 1 (2.1%) | 0 (0.0%) | 12 (25.5%) | 35 (74.5%) | 0 (0.0%) | 47 |

CV=Cardiovascular, HF=Heart Failure, txs=transmissions
### Table S3. Maximum Triage-HFRS within 30-day diagnostic evaluation and associated non-elective hospitalisations (APC and A&E episodes)

| 30-day Diagnostic Evaluation Period Max Triage-HFRS | Total diagnostic evaluation periods | 30-day Outcomes |
|---------------------------------------------------|------------------------------------|-----------------|
|                                                   | All-cause hospitalisation (APC or A&E) | Cardiovascular hospitalisation (APC or A&E) | HF hospitalisation (APC only) |
| Low                                               | 2288 (33.6%) 98 (4.3%)               | 24 (1.0%)       | 6 (0.3%) |
| Medium                                            | 3535 (51.8%) 175 (5.0%)             | 48 (1.4%)       | 7 (0.2%) |
| High                                              | 996 (14.6%) 111 (11.2%)             | 42 (4.2%)       | 23 (2.3%) |
| Total                                             | 6819 (100%) 384 (5.6%)             | 114 (1.7%)      | 36 (0.5%) |

*APC = admitted patient care episode, HFRS = heart failure risk score, A&E = accident and emergency*
### Table S4. Demographics of patients with at least one 30-day hospitalisation outcome in prospective analysis (APC and A&E episodes)

|                      | All-cause hospitalisation | Cardiovascular hospitalisation | HF hospitalisation | All patients |
|----------------------|---------------------------|--------------------------------|-------------------|--------------|
| Patients, n (%)      | 206                       | 81                             | 28                | 429          |
| Age, mean (sd)       | 67.3 (16.5)               | 69.4 (16.7)                    | 76.8 (9.8)        | 66.0 (15.5)  |
| Male, n (%)          | 135 (65.5%)               | 60 (74.1%)                     | 18 (64.3%)        | 271 (63.2%)  |
| Device Type, n (%)   |                           |                                |                   |              |
| CRT-D                | 82 (39.8%)                | 33 (40.7%)                     | 12 (42.9%)        | 162 (37.8%)  |
| CRT-P                | 84 (40.8%)                | 32 (39.5%)                     | 13 (46.4%)        | 168 (39.02%) |
| ICD                  | 19 (9.2%)                 | <5 (<5.0%)                     | <5 (<17.9%)       | 36 (8.4%)    |
| PPM                  | 21 (10.2%)                | >11 (>13.6%)                   | <5 (<17.9%)       | 63 (14.7%)   |
| NYHA                 |                           |                                |                   |              |
| No heart failure     | 25 (12.1%)                | 10 (12.3%)                     | <5 (<17.9%)       | 62 (14.5%)   |
| 1                    | 19 (9.2%)                 | 8 (9.9%)                       | <5 (<17.9%)       | 53 (12.4%)   |
| 2                    | 72 (35.0%)                | 24 (29.6%)                     | 5 (17.9%)         | 150 (35.0%)  |
| 3+                   | 79 (38.3%)                | 36 (44.4%)                     | 21 (75.0%)        | 142 (33.1%)  |
| CKD stage 3 or higher| 73 (35.4%)                | 36 (44.4%)                     | 18 (64.3%)        | 132 (30.8%)  |

*HF = heart failure, CRT-D = cardiac resynchronisation therapy device with defibrillator, CRT-P = cardiac resynchronisation therapy device with pacemaker, ICD = implanted cardiac defibrillator, PPM = pacemaker, NYHA = New York Heart Association Functional Classification, CKD = chronic kidney disease*
Table S5. Coefficients of frailty model using A&E and APC episodes as a combined outcome

| Variable          | All-cause hospitalisation within 30 days | Cardiovascular hospitalisation within 30 days |
|-------------------|-----------------------------------------|---------------------------------------------|
|                   | Hazard Ratio   | 95% CI    | p-value | Hazard Ratio   | 95% CI    | p-value |
| Medium (vs Low)   | 0.986         | 0.748 – 1.301 | 0.92 | 1.150         | 0.676 – 1.959 | 0.61 |
| High (vs Low)     | **2.049**     | 1.474 – 2.846 | **<0.001** | **3.320** | 1.845 – 5.974 | **<0.001** |
| No HF             | 1.148         | 0.623 – 2.113 | 0.66 | 1.012         | 0.343 – 2.983 | 0.98 |
| Age               | 1.001         | 0.990 – 1.013 | 0.663 | 1.014         | 0.994 – 1.023 | 0.19 |
| CRTP vs CRTD      | 0.699         | 0.487 – 1.002 | 0.05 | 0.662*        | 0.754 – 2.166 | 0.26 |
| PPM vs CRTD       | **0.478**     | 0.254 – 0.898 | **0.02** | 0.841*        | 0.262 - 2.698 | 0.77 |
| ICD vs CRTD       | 0.562         | 0.280 - 1.124 | 0.10 | 0.169*        | 0.019-1.468 | 0.11 |
| CKD stage 3 or higher | 1.326 | 0.931 – 1.890 | 0.12 | 1.559*        | 1.054 – 2.306 | 0.06 |

*HF = heart failure, CRT-D = cardiac resynchronisation therapy device with defibrillator, CRT-P = cardiac resynchronisation therapy device with pacemaker, ICD = implanted cardiac defibrillator, PPM = pacemaker, CKD = chronic kidney disease*
Table S6. Coefficients for time-varying covariate frailty model for cardiovascular hospitalisation within 30-days (APC and A&E as a joint outcome)

| Variable                        | Cardiovascular hospitalisation within 30 days |
|---------------------------------|-----------------------------------------------|
|                                 | Hazard Ratio | 95% CI  | p-value  |
| Medium (vs Low)                 | 1.150        | 0.676 – 1.959 | 0.61     |
| High (vs Low)                   | **3.320**    | 1.845 – 5.974 | <0.001   |
| No HF                           | 1.012        | 0.343 - 2.983 | 0.98     |
| Age                             | 1.014        | 0.994 – 1.023 | 0.19     |
| CRTP vs CRTD (0-15 days)        | 0.662        | 0.754 – 2.166 | 0.26     |
| PPM vs CRTD (0-15 days)         | 0.841        | 0.262 - 2.698 | 0.77     |
| ICD vs CRTD (0-15 days)         | 0.169        | 0.019-1.468   | 0.11     |
| CKD stage 3 or higher (0-15 days)| 1.559      | 1.054 – 2.306 | 0.06     |
| CRTP vs CRTD (16-30 days)       | 0.598        | 0.261 - 1.369 | 0.22     |
| PPM vs CRTD (16-30 days)        | 0.456        | 0.130 - 1.602 | 0.22     |
|                        |       |                |        |
|------------------------|-------|----------------|--------|
| ICD vs CRTD (16-30 days) | 2.277 | 0.220 - 23.527 | 0.49   |
| CKD stage 3 or higher (16-30 days) | 0.564 | 0.261 - 1.217  | 0.14   |

HF = heart failure, CRT-D = cardiac resynchronisation therapy device with defibrillator, CRT-P = cardiac resynchronisation therapy device with pacemaker, ICD = implanted cardiac defibrillator, PPM = pacemaker, CKD = chronic kidney disease
Table S7. Costs for hospitalisations in the retrospective analysis

| Max risk in previous 30 days | Low | Medium | High | No transmission |
|-----------------------------|-----|--------|------|-----------------|
|                            | N   | Cost   | Missing | N   | Cost   | Missing | N   | Cost   | Missing |
| A&E episodes                |     |        |         |     |        |         |     |        |         |
| All-cause                   | 78  | £9,107 | 0       | 115 | £14,057 | 1       | 52  | £6,583 | 0       |
| Cardiovascular              | 11  | £1,491 | 0       | 26  | £3,671 | 0       | 17  | £2,470 | 0       |
| Total costs (APC and A&E episodes combined) |     |        |         |     |        |         |     |        |         |
| All-cause                   | 151 | £181,986 | 1 | 261 | £389,896 | 4 | 184 | £437,367 | 4 | 10 | £10,312 | 2 |
| Cardiovascular              | 31  | £58,403 | 0       | 81  | £139,897 | 0       | 67  | £156,622 | 0       | 4  | £6,250  | 0       |
| HF                          | 5   | £14,676 | 0       | 12  | £40,230 | 0       | 28  | £94,135 | 0       | 2  | £5,774  | 0       |

*APC = admitted patient care episode, HFRS = heart failure risk score, A&E = accident and emergency, HF = heart failure*
Table S8. Costs for A&E and APC events within the prospective analysis

| 30-day Diagnostic Evaluation Period | Total diagnostic evaluation periods | All-cause hospitalisation | Cardiovascular hospitalisation | HF hospitalisation |
|------------------------------------|------------------------------------|---------------------------|-------------------------------|-------------------|
| Max Triage-HFRS                    | N                                  | Total Cost                | Missing | Average Cost | N | Total Cost | Average Cost | N | Total Cost | Average Cost |
| Low                                | 2282 (33.6%)                       | £95,133                   | 2       | £990.97      | 24 | £35,173   | £1,465.55    | 6 | £18,561    | £3,093.50    |
| Medium                             | 3530 (51.8%)                       | £231,701                  | 1       | £1,324.01    | 48 | £84,819   | £1,767.07    | 7 | £19,142    | £2,734.58    |
| High                               | 993 (14.6%)                        | £257,354                  | 2       | £2,361.05    | 42 | £103,832  | £2,472.20    | 23 | £80,438    | £3,497.31    |
| Total                              | 6805 (100%)                        | £584,188                  | 5       | £1,541.40    | 114| £223,824  | £1,963.37    | 36 | £118,141   | £3,281.70    |

HF = heart failure, HFRS = heart failure risk score. No missing data for cardiovascular and HF hospitalisation costs.
Table S9. Cardiovascular coding according to ICD10 codes and SUSHRG codes for non-elective APC episodes (All-cause hospitalisation)

| SUSHRG coding       | ICD10 coding               |
|---------------------|----------------------------|
|                     | Cardiovascular: HF | Cardiovascular: Non-HF | Non-Cardiovascular |
| Cardiovascular: HF  | 47                        | 0                        | 0                   |
| Cardiovascular: Non-HF | 3                      | 73                       | 7                   |
| Non-Cardiovascular  | 0                        | 4                        | 229                 |

ICD-10 = International Statistical Classification of Diseases and Related Health Problems (10th revision), SUSHRG = Secondary Uses Service generated Healthcare Resource Group code, HF = heart failure
Table S10. Demographics of patients with at least one 30-day hospitalisation outcome in prospective analysis (APC only)

|                       | All patients | All-cause hospitalisation | Cardiovascular hospitalisation | HF hospitalisation |
|------------------------|--------------|----------------------------|--------------------------------|-------------------|
| **Patients, n (%)**    | 429          | 138                        | 65                             | 24                |
| **Age, mean (sd)**     | 66.0 (15.5)  | 70.1 (14.7)                | 70.3 (16.2)                    | 76.3 (10.0)       |
| **Male, n (%)**        | 271 (63.2%)  | 91 (65.9%)                 | 48 (73.8%)                     | 14 (58.3%)        |
| **Device Type, n (%)** |              |                            |                                |                   |
| CRT-D                  | 162 (37.8%)  | 60 (43.5%)                 | 26 (40.0%)                     | 9 (37.5%)         |
| CRT-P                  | 168 (39.02%) | 57 (41.3%)                 | 27 (41.5%)                     | 12 (50.0%)        |
| ICD                    | 36 (8.4%)    | 7 (5.1%)                   | <5 (<7.7%)                     | <5 (<20.8%)       |
| PPM                    | 63 (14.7%)   | 14 (10.1%)                 | >5 (>7.7%)                     | <5 (<20.8%)       |
| **NYHA**               |              |                            |                                |                   |
| No heart failure       | 62 (14.5%)   | 13 (9.4%)                  | 8 (12.3%)                      | <5 (<20.8%)       |
| 1                      | 53 (12.4%)   | 8 (5.8%)                   | 5 (7.7%)                       | <5 (<20.8%)       |
| 2                      | 150 (35.0%)  | 52 (37.7%)                 | 21 (32.3%)                     | 5 (20.8%)         |
| 3+                     | 142 (33.1%)  | 59 (42.8%)                 | 28 (43.1%)                     | 17 (70.8%)        |
| Missing                | 22 (5.1%)    | 6 (4.3%)                   | 3 (4.6%)                       | 0 (0.0%)          |
| **CKD stage 3 or higher** | 132 (30.8%) | 53 (38.4%)                 | 29 (44.6%)                     | 16 (66.7%)        |
| Missing: 4 (0.9%)      |              |                            |                                |                   |
| Missing: 2 (1.4%)      |              |                            |                                |                   |

HF = heart failure, CRT-D = cardiac resynchronisation therapy device with defibrillator, CRT-P = cardiac resynchronisation therapy device with pacemaker, ICD = implanted cardiac defibrillator, PPM = pacemaker, NYHA = New York Heart Association Functional Classification, CKD = chronic kidney disease
Table S11. Coefficients for time-varying covariate frailty model for cardiovascular hospitalisation within 30-days

| Variable                  | Hazard Ratio | 95% CI       | p-value |
|---------------------------|--------------|--------------|---------|
| Medium (vs Low)           | 1.059        | 0.758–1.481  | 0.74    |
| High (vs Low)             | 2.410        | 1.653–3.512  | <0.001  |
| No HF                     | 1.063        | 0.411–2.755  | 0.90    |
| Age                       | 1.015        | 0.998–1.033  | 0.08    |
| CRTP vs CRTD (0-15 days)  | 0.653        | 0.373–1.146  | 0.14    |
| PPM vs CRTD (0-15 days)   | 0.352        | 0.127–0.973  | 0.04    |
| ICD vs CRTD (0-15 days)   | 0.247        | 0.080–0.760  | 0.01    |
| CKD stage 3 or higher     | 1.379        | 0.800–2.377  | 0.25    |
| CRTP vs CRTD (16-30 days) | 0.789        | 0.484–1.288  | 0.34    |
| PPM vs CRTD (16-30 days)  | 0.579        | 0.201–1.674  | 0.31    |
| ICD vs CRTD (16-30 days)  | 0.489        | 0.099–2.440  | 0.38    |
| CKD (16-30 days) | 1.273 | 0.795 – 2.041 | 0.32 |

HF = heart failure, CRT-D = cardiac resynchronisation therapy device with defibrillator, CRT-P = cardiac resynchronisation therapy device with pacemaker, ICD = implanted cardiac defibrillator, PPM = pacemaker, CKD = chronic kidney disease
Table S12. Costs for APC hospitalisations in the prospective analysis

| 30-day Diagnostic Evaluation Period Max Triage-HFRS | Total diagnostic evaluation periods | All-cause hospitalisation | Cardiovascular hospitalisation | HF hospitalisation |
|---------------------------------------------------|-------------------------------------|---------------------------|--------------------------------|-------------------|
| N | Total Cost | Missing | Average Cost | N | Total Cost | Missing | Average Cost | N | Total Cost | Missing | Average Cost |
|---|-------------|---------|--------------|---|-------------|---------|--------------|---|-------------|---------|--------------|
| Low | 2288 (33.6%) | 46 (2.0%) | £93,604 | 6 | £2,340.10 | 16 (0.7%) | £38,929 | 0 | £2,433.07 | 6 (0.3%) | £19,353 | 0 | £3,225.50 |
| Medium | 3535 (51.8%) | 97 (2.7%) | £209,337 | 18 | £2,649.84 | 38 (1.1%) | £80,898 | 4 | £2,379.35 | 6 (0.2%) | £13,055 | 2 | £3,263.75 |
| High | 996 (14.6%) | 85 (8.5%) | £245,924 | 17 | £3,616.53 | 35 (3.5%) | £104,274 | 3 | £3,258.57 | 20 (2.0%) | £72,703 | 1 | £3,826.48 |
| Total | 6819 (100%) | 228 (3.3%) | £548,865 | 41 | £2,935.11 | 89 (1.3%) | £224,101 | 7 | £2,732.94 | 32 (0.5%) | £104,481 | 3 | £3,602.80 |

HF = heart failure, HFRS = Heart failure risk score, APC = admitted patient care episode
### Table S13. Costs for APC hospitalisations in the retrospective analysis

| Max risk in previous 30 days | Low | Medium | High | No transmission |
|-----------------------------|-----|--------|------|-----------------|
|                            | N   | Cost   | Missing | N   | Cost   | Missing | N   | Cost   | Missing |
| All-cause                   | 72  | £172,879 | 1 | 146  | £375,839 | 3 | 132  | £430,784 | 4 | 8  | £10,091 | 2 |
| Cardiovascular              | 20  | £56,912  | 0 | 55   | £136,226 | 0 | 50   | £154,152 | 0 | 3  | £6,120  | 0 |
| HF                          | 5   | £14,676  | 0 | 12   | £40,230  | 0 | 28   | £94,135  | 0 | 2  | £5,774  | 0 |

*HF = heart failure, APC = admitted patient care episode*
### Table S14. Device type and NYHA class

| NYHA | CRT-D | CRT-P | ICD | PPM |
|------|-------|-------|-----|-----|
| No HF | <5 | 15 | >6 | 37 |
| 1 | >23 | 13 | 6 | >5 |
| 2 | 67 | 63 | 12 | 9 |
| 3+ | 67 | 72 | <6 | <5 |

HF = heart failure, CRT-D = cardiac resynchronisation therapy device with defibrillator, CRT-P = cardiac resynchronisation therapy device with pacemaker, ICD = implanted cardiac defibrillator, PPM = pacemaker, NYHA = New York Heart Association Functional Classification
Table S15. Diagnosis codes which led to incongruent cardiovascular classification for non-elective APC episodes (ACH)

| ICD10 code | ICD10 Rubric | ICD10 categorisation | SUSHRG code | SUSHRG Rubric | SUSHRG categorisation |
|------------|--------------|----------------------|-------------|---------------|-----------------------|
| K59.0      | Constipation | Non-cardiovascular   | EB10        | Actual or suspected Myocardial infarction | Cardiovascular       |
| I95.9      | Hypotension, unspecified | Non-cardiovascular | EB14        | Other acquired cardiovascular conditions | Cardiovascular       |
| I95.1      | Orthostatic hypotension | Cardiovascular | DZ65        | COPD          | Non-cardiovascular    |
| T82.7      | Infection and inflammatory reaction due to other cardiovascular and vascular devices, implants and grafts | Cardiovascular | YR44        | Removal of central venous catheter | Non-cardiovascular   |
| I25.1      | Atherosclerotic heart disease | Cardiovascular | YF01        | Radiological insertion of gastronomy tube | Non-cardiovascular   |
| I42.0*     | Dilated cardiomyopathy | Cardiovascular | UZ01        | Data invalid for grouping | Non-cardiovascular   |
| R05*       | Cough        | Non-cardiovascular   | EB12        | Unspecified chest pain | Cardiovascular       |
| ICD-10 Code | Disease Description                                      | Category               |
|-------------|----------------------------------------------------------|------------------------|
| R06.0*      | Dyspnoea                                                 | Non-cardiovascular      |
| J45.9*      | Asthma, unspecified                                      | Non-cardiovascular      |
| C79.5*      | Secondary malignant neoplasm of bone and bone marrow     | Non-cardiovascular      |
| J44.9*      | Chronic obstructive pulmonary disease, unspecified       | Non-cardiovascular      |
| I50.0*      | Congestive heart failure                                 | Cardiovascular: HF      |

ICD-10 = *International Statistical Classification of Diseases and Related Health Problems (10th revision), SUSHRG = Secondary Uses Service generated Healthcare Resource Group code, HF = heart failure

*second ICD-10 code as first code was not categorisable.
Figure S1. Selection process for (left:) APC episodes between 1 Jan 2017 and 31 Dec 2018 and (right:) A&E attendances between 1 Jan 2017 and 31 Dec 2018

HF = heart failure, APC = admitted patient care, HFRS = heart failure risk score
Figure S2. Cumulative event rates for hospitalisation after first high, where hospitalisation can be an A&E attendance or an APC episode. Following their first high, a substantial number of patients experienced an all-cause hospitalisation within days, but this was not observed for the first cardiovascular hospitalisations following the first high episode.
Figure S3. Cumulative probability curves for hospitalisation in prospective analysis, where hospitalisation can be an A&E attendance or an APC episode. The high-risk group had higher incidence rates beyond 3 days compared with medium- and low-risk groups.

ACH = all-cause hospitalisation, CVH = cardiovascular hospitalisation, HFH = heart failure hospitalisation