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ORIGINAL RESEARCH ARTICLE

Assessing the Expected Costs of Continuous Remote Monitoring for Post-Discharge Home Use and the Readmission Reduction Required to Achieve Cost Neutrality

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Abstract

Background/Objective Hospital-level care at home is gaining traction, but evidence on health economic implications remains limited. The aim of this study was to estimate expected costs of continuous remote monitoring of vital signs in the post-discharge setting, to assess the burden of readmissions among relevant patient groups, and to compare monitoring costs with the potential savings from reduced readmissions. The study was conducted from a restricted societal perspective within the Danish healthcare system.

Methods The costs of 3-day post-discharge home monitoring were estimated using a micro-costing approach based on the WARD-Home project. The analysis excluded healthcare costs incurred outside the hospital sector or beyond the 3-day period. Readmission rates, length of stay, and associated costs were analyzed using Danish registry data on patients potentially suitable for post-discharge monitoring but currently not receiving it.

Results Estimated per-patient costs of 3-day monitoring were EUR 159. Registry data showed an overall 3-day readmission rate of 1.7%, with average length of stay of 4.4 days, and costs of EUR 4674. Comparing average costs of readmissions within 3 days—corresponding to monitoring duration—with the monitoring costs indicated that if post-discharge monitoring reduces readmissions, cost-neutrality could be achieved if it prevents one readmission in every 29 patients monitored.

Conclusions Continuous remote monitoring offers a solution to post-discharge patients at risk of short-term deterioration and readmission. If one readmission is prevented per every 29 patients monitored, the approach has the potential to achieve cost-neutrality. Future studies are needed to validate these estimates and determine whether reductions in readmissions and actual cost savings can be achieved in practice.

Key Points for Decision-Makers

Post-discharge continuous remote monitoring incurs an incremental cost of EUR 159 per patient during a 3-day monitoring period.

If one readmission within 3 days post-discharge can be prevented for every 29 patients monitored, the approach could achieve cost-neutrality; however, further research is required to determine whether this holds true in practice and whether actual savings can be realized.

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1 Introduction

The trend toward delivering hospital-level care in the patient's home is gaining momentum as healthcare systems are increasingly facing resource and capacity constraints. Home-based care is not a recent development as such, however, the rapid evolution of healthcare technologies has increased the range of hospital-level services that can be provided in the patient's home. This includes regular outpatient procedures, such as chemotherapy administration by programmable infusion pumps [1] and intravenous administration of antibiotics [2], remote monitoring of patients with chronic diseases [3, 4] and postoperative patients [5, 6], and even full hospitalization at home [7]. The latter is referred to as Hospital at Home (HaH) and can be defined as "an acute clinical service that takes staff, equipment, technologies, medication, and skills usually provided in hospitals and delivers that hospital care to selected people in their homes or in nursing homes. It substitutes for acute inpatient hospital care" [7]. Advancements in sensor technology, wireless communication, and data analytics have enabled new ways to monitor and manage patient health remotely [8] and thus, play a central role in enabling and supporting the growth of HaH services. Innovative monitoring technologies offer continuous surveillance of patients' health metrics with real-time alarms through machine learning (ML) algorithms, supporting clinical decision-making from a distance. Thus, the HaH model supported by cutting-edge technology represents a promising shift toward more accessible and efficient care.

One example of a HaH model supported by continuous monitoring technology is the WARD-Home project, an ongoing research initiative implementing advanced artificial intelligence (AI)-algorithm augmented 24/7 monitoring of patient's vital signs in patient's home immediately following discharge from medical treatment [9]. The monitoring technology used in WARD-Home is the WARD Clinical Support System (WARD-CSS), which is designed for both in-hospital and home-based use. In WARD-Home, continuous remote monitoring by WARD-CSS targets patients recently discharged after hospitalization who are at risk of short-term clinical deterioration and hospital readmission. The intervention may also be deemed relevant in cases of acute illness where it is determined that immediate hospital treatment is not required, allowing the patient to remain at home (admission avoidance model).

Implementing a HaH model supported by WARD-CSS or similar decision-support systems may entail considerable initial expenses owing to necessary technology investments and training for healthcare staff. This model requires purchasing advanced equipment for continuous remote monitoring, along with preparing staff to adapt to new workflows and the shift from traditional in-hospital care to home-based care delivery. However, the initial expenses may be offset by the (potential) benefits of the system, such as decreased length of stay (LOS) and reduced readmissions. Understanding the economic impact is, thus, crucial for informed investment decisions. Different HaH models have been studied in literature that suggest similar or improved mortality and readmission rates, reduced LOS, and higher patient satisfaction compared with conventional inpatient care [10]. Regarding resource use and costs, the evidence is inconclusive [10]. A recent systematic review by Patel et al. [11] studied remote vital signs monitoring in HaH models specifically and found comparable 3-month readmission rates and 6-month mortality rates. While these findings were based on studies of both intermittent and continuous remote monitoring, the analyses focused on continuous remote monitoring (combined with nurse and physician home visits, video communication, intravenous medications, and point-of-care-testing) indicated a potential association with reduced readmission rates and healthcare costs [12, 13]. Specifically, mean cost was 38% lower for home patients compared with patients receiving usual care in the hospital ($p < 0.001$), and these patients also had lower readmission rates (7% versus 23%) [12]. Further recent studies, not included in the review by Patel et al. (2024), have suggested potential benefits of remote vital signs monitoring in specific patient groups. One observational study demonstrated reduced readmission rates following outpatient total joint arthroplasty [14]. In addition, Mokri et al. (2024) presented a modeled cost-effectiveness analysis showing that remote monitoring of heart failure (HF) patients' vital signs resulted in reduced HF-related hospitalization costs and may be cost-effective from both a healthcare and a societal perspective [15].

This study aims to estimate the expected costs of advanced continuous remote monitoring in the post-discharge home setting and to assess its potential to reduce readmissions from a restricted societal perspective within the Danish healthcare system. First, we use a micro-costing approach to estimate the per-patient costs of continuous remote monitoring following discharge, using the WARD-Home project as a case. Second, we analyze the burden of readmissions—measured by readmission rates, LOS, and costs of readmission—in selected patient groups in order to estimate the potential for reducing readmissions by post-discharge monitoring. The analysis of readmissions is on the basis of Danish registry data of patients who could be eligible for remote monitoring post-discharge but have not received it. Finally, we compare the costs of continuous remote monitoring in the post-discharge home setting with the potential savings if readmissions can be reduced.

2 Methods

The study is part of the Wireless Assessment of Respiratory and circulatory Distress (WARD) Home project conducted at Bispebjerg Hospital and Rigshospitalet, Denmark. WARD-Home involves continuous remote monitoring of patients' vital signs by wireless devices and with the integration of AI to detect imminent clinical deterioration.

2.1 Cost Estimation

The first part of the study is the estimation of costs associated with continuous remote monitoring in the post-discharge home setting. The cost estimation is based on the WARD-Home project, in which the WARD-CSS is employed to monitor patients for a period of 3 days following hospital discharge (see below). The costs of WARD-CSS for post-discharge home monitoring are compared against current practice, defined as patient discharge without subsequent monitoring. The cost estimation is conducted from a restricted societal perspective, encompassing healthcare costs incurred within the hospital sector and transportation costs, irrespective of the payer. As a result, the analysis excludes potential downstream costs occurring outside the hospital sector or beyond the 3-day post-discharge period.

2.1.1 Continuous Remote Monitoring by WARD-CSS

WARD-CSS facilitates the continuous monitoring of patients' vital signs in their homes immediately following hospital discharge or in cases where hospital admission is not required, and the patient may be admitted to his/her own home instead. Patients are equipped with vital signs monitoring devices and provided with a tablet before returning home. The equipment is installed at the hospital by a nurse and additional time is allocated for training the patient in the use and management of the equipment at home. The monitoring system includes a wristband with a sensor for measuring oxygen saturation, a reusable chest single-lead electrocardiogram-patch, and a blood pressure cuff with an attached pouch to hold the monitoring device. During the monitoring period, the patient may need to return to the hospital for a clinical evaluation, potentially leading to (re) admission. After the completion of the monitoring period, the patient removes the equipment, and a nurse retrieves the equipment in the patient's home. If a patient is readmitted during the monitoring period, the monitoring equipment is removed at the hospital.

2.1.2 The WARD-Home Project

In a recent observational feasibility study within the WARD-Home project, the WARD-CSS for continuous remote monitoring was piloted in medical patients aged 18 years and older discharged to their home [16]. The aim of the study was to assess feasibility, defined as the number of minutes in the measuring interval with complete monitoring data. Details on the practical execution of the WARD-Home study provided foundational data for the cost estimation. To support the cost estimation, interviews were conducted with one clinician and one nurse from the WARD-Home team to review resource utilization related to monitoring during the study. In the WARD-Home study, monitoring was conducted over a 3-day period following discharge. Three days were selected owing to the battery limitations of the electrocardiogram device. During the 3-day monitoring period, hospital nurses were responsible for responding to any alarms triggered by the monitoring system. When an alarm is activated, the nurse must evaluate its relevance, often requiring a review of the patient's medical records. If the alarm warranted a response, the nurse contacted the patient by phone. In cases where the nurse, in consultation with a physician, determined that a physical assessment was necessary, the patient was instructed to return to the hospital. Depending on the patient's condition and circumstances, they might travel to the hospital independently, be transported by a relative, take a taxi, use patient transport, or be transported by ambulance if lying down or receiving treatment during transit was required. At the hospital, the hospital staff would determine whether the patient required (re)admission or if they could return home.

2.1.3 Cost of Continuous Remote Monitoring by WARD-CSS

Cost data on WARD-CSS for post-discharge home use was collected using a micro-costing approach. An interview was conducted with one clinician and one nurse representing the WARD-Home project and provided estimates on resource use on the basis of the observational WARD-Home study. Additional members of the WARD-Home project team (the authors EKA and CSM) validated and added to the cost estimation. Time spent on installation of the monitoring devices was derived from a recent paper by the WARD-Home project team [17]. Costs were then calculated by multiplying the estimated time spent on monitoring tasks by average time cost plus average transportation costs, irrespective of the payer, which are available from guidelines provided by the Danish Medicines Council [18]. The assumed list price of

the system was determined by HumanBytes.[1] The number of transports to the hospital that do not require hospital admission was based on assumptions. We considered three distinct scenarios of the costs of continuous remote monitoring by WARD-CSS: a base case scenario, a low-cost scenario, and a high-cost scenario. The three scenarios differ on the basis of time used for instruction of the patient, number of alarms, and assumptions regarding the extent of hospital transports that do not result in a readmission. In the base case scenario, we assumed an equal number of transports leading to either readmission or discharge. In the low-cost scenario, we reduced the number of transports resulting in readmission to half of those leading to discharge. In the high-cost scenario, we assumed a higher number of transports resulting in readmission, specifically twice the readmission rate compared with discharge. The assumed readmission rate used for these calculations was the overall 3-day readmission rate (corresponding to the monitoring period) derived from the registry-based analysis (see Sect. 2.2).

2.2 Registry-Based Analysis of Readmissions

The second part of the study is the registry-based analysis of readmissions. This analysis was performed using Danish registry data on patients potentially relevant for post-discharge home monitoring. The patients were selected on the basis of a previous study [19], which reported a high frequency of emergency service contacts and an elevated risk of readmissions, thereby identifying them as appropriate patients for the current study. As the observational WARD-Home study was not completed at the time of analysis, it was not possible to obtain registry data on the participants in this study. Consequently, the registry-based analysis includes patients previously discharged from the hospital without post-discharge monitoring.

2.2.1 Study Population and Identification of Admissions and Readmissions

In-patient admissions were retrieved for 2018 from the National Patient Registry (NPR), which holds information on all inpatient care in Danish general public hospitals, including all types of admissions, diagnoses, treatments, surgeries, and other procedures. Using the central personal registration number, which is unique for every Danish citizen, each patient was linked to additional registries to retrieve sociodemographic data and data on costs of admissions. Patients were included if they were ≥ 18 years old and had a hospital admission during 2018 in a general public hospital. Exclusion criteria included individuals with incomplete or unavailable data, and those who could not be identified within the population registries. In cases where sociodemographic data for the index year was missing, the most recent data available within the preceding 2 years was utilized. If no data were available within this timeframe, the patient was categorized as having missing information and excluded from the analysis. The Charlson Comorbidity Index (CCI) was calculated on the basis of documented diagnoses from the 5 years preceding the date of each primary admission. Consequently, patients may have different CCI scores if they experienced multiple primary admissions within this timeframe. In addition, patients who died within 30 days of discharge were excluded, as their potential for readmission could not be assessed in these cases.

Primary admission could be either emergency or planned but must have a minimum length of 12 h. On the basis of primary admissions, we selected 20 patient groups potentially relevant for continuous remote monitoring after discharge from hospital admission. The 20 patient groups were defined by major medical diagnoses codes based on International Classification of Diseases (ICD) 10th revision (ICD-10) [20] and surgical procedures codes based on the Nordic Medico-Statistical Committee (NOMESCO) Classification of Surgical Procedures [21]. If a patient had multiple contacts during one admission, we used the primary diagnosis code of the first contact. If a patient met the criteria for both the medical and surgical groups, they were allocated to the surgical group. This was done because the surgical group encompasses major procedures, which are likely to be the primary reason for admission, overriding the underlying medical diagnosis. Table 1 presents the patient groups and the defining diagnosis and procedure codes. These definitions are similar to those reported in Sigvardt et al. [19].

Readmissions were defined as any emergency admission within 30 days of previous discharge date. Contacts with less than 4 h between admission and previous discharge were considered one admission. Hence, an admission could only be considered a readmission if it occurred > 4 h after discharge. After identifying primary admissions and readmissions, we applied a wash-out period of 30 days to ensure that we did not count any readmissions in the study period as a primary admission. Short-term readmissions were then operationalized as readmissions within 1, 2, 3, and 7 days from the previous discharge date. In the primary analysis, we examined 3-day and 30-day readmissions following any type of primary admission. In a subsequent analysis, we divided readmissions into two categories: those following a planned hospital admission and those following an emergency hospital admission. Each patient may appear multiple times in the dataset if they were admitted multiple times during 2018.

[1] Company specializing in selling AI solutions for the healthcare sector and provider of WARD-CSS.

Table 1 Selected patient groups and included diagnosis and procedure codes

Medical diagnosis groups	Diagnosis codes (ICD-10)	Surgical procedure groups	Procedure codes (NOMESCO)
Infectious diseases	DA	Intracranial surgery	KA
Cancer[a]	DC-DD	Heart surgery[d]	KF
Endocrine diseases	DE	Surgery on respiratory organs, mediastinum, and diaphragm	KG
Vascular and infectious diseases of the brain	DG+DI600-649	Colorectal resections	KJFB KJFH KJGB
Myocardial infarction	DI21, DI210-213C	Other major abdominal surgery[e]	KJ
Other diseases of the circulatory system[b]	DI	Surgery on genitourinary system	KK
AECOPD[c]	DJ440, DJ441	Surgery on female reproductive organs	KL
Other diseases of the respiratory system[c]	DJ	Vascular surgery	KP
Diseases of the gastrointestinal system	DK	Hip and knee replacement surgery	KNFB KNFC KNGB KNGC
Diseases of the genitourinary system	DN	Other orthopedic surgery[f]	KN

AECOPD, chronic obstructive pulmonary disease (COPD) with either acute exacerbation or acute lower respiratory infection; ICD-10, International Classification of Diseases 10th revision; NOMESCO, Nordic Medico-Statistical Committee Classification of Surgical Procedures

[a]Includes anemia and neutropenia

[b]Not DI21, DI210-213C + DI600-649

[c]Not DJ440 + DJ441

[d]Including the intrathoracic great vessels

[e]Not KJFB, KJFH, or KJGB

[f]Not KNFB, KNFC, KNGB, or KNGC

2.2.2 Burden of Readmissions

We examined the burden of readmissions by estimating the readmission rates, as well as the average duration of a readmission and the average cost of a readmission, among the selected patient groups. Readmission rates were calculated as the percentage of patients within the respective groups who were readmitted. LOS was calculated as the difference in days between admission date and discharge date. Costs of readmissions were estimated using diagnosis-related groups (DRG) tariffs. As available registries do not contain information on exact treatment costs, we relied on the DRG tariffs, which represent the average treatment costs of specific DRG groups. These data are available from the DRG-coded NPR [22]. DRG groups are groups of patients who are similar in terms clinical characteristic and resource use. The DRG tariffs encompass direct (such as care and treatment) and indirect non-healthcare (such as administration) costs, as well as most operating costs (such as rent). By linking cost data and activity data, an average cost for each particular DRG group can be derived [23].

The average LOS and the average costs of a readmission were estimated for each group, across all 20 groups and for each timeframe (1, 2, 3, 7, and 30 days). This was done by calculating the cost and LOS, respectively, of each readmission and then averaging over all patients in the respective groups and in the full sample.

All costs have been adjusted to 2024-price levels using the consumer price index [24] and converted to Euros (1 EUR = 7.45 DKK).

Data management, analyses, and graphic illustrations were performed using Stata V.17.

3 Results

3.1 Cost Estimation of Continuous Remote Monitoring by WARD-CSS for Post-Discharge Home Use

The costs of WARD-CSS for post-discharge home monitoring comprise the following cost items: the list price of the system—including software licenses, onboarding and training healthcare staff, support and upgrades,

maintenance contract, and time for device care;[2] monitoring devices; server installation for data storage; time spent by the nurse on installing the monitoring equipment and instructing the patient; time spent by the nurse on handling alarms; transportation to the hospital if a clinical evaluation is required; cost of the clinical evaluation; and time spent by the nurse on removing the monitoring devices in the patient's home (if not readmitted). The values and costs assigned to each of these items in each scenario are presented in Table 2 along with the source of the information.

Table 3 presents the total costs of WARD-CSS for post-discharge home monitoring in the three scenarios. The scenarios proceed as described in the Methods section. They vary according to time spent on instructing the patient, the number of alarms, and the number of transportations to the hospital not resulting in a readmission. Total costs were estimated per patient monitored over the 3-day period. A detailed description of the cost calculation can be found in Online Resource 1 (Table S2).

The cost of WARD-CSS for post-discharge home monitoring was EUR 159 in the base case scenario, ranging from EUR 109 in low-cost scenario to EUR 217 in the high-cost scenario.

3.2 Registry-Based Analysis of Readmissions

3.2.1 Patient Characteristics and Distribution

Table 4 presents the characteristics of the included patients divided into patients who are not readmitted, patients who are readmitted within 3 days, and patients who are readmitted within 30 days post-discharge.

The sample comprised a total of 285,930 patients, of whom 4816 (1.7%) were readmitted within 3 days of discharge and 21,302 (7.5%) were readmitted within 30 days of discharge. Compared with patients who were not readmitted, those readmitted within 3 or 30 days shared broadly similar characteristics, though with slight variations in magnitude. For 3-day readmissions, patients were slightly older (64.5 versus 64.0 years), more often male (52.0% versus 49.5%), less frequently employed (25.4% versus 27.8%), and more often received social pension (55.0% versus 51.8%) compared with those not readmitted. In addition, patients readmitted within 3 days had higher CCI values than patients not readmitted at all (39.8% versus 36.9% with a CCI > 0). Similarly, patients with 30-day readmissions were older than patients not readmitted at all (66.7 years versus 64.0 years), more often males (52.0% versus 49.5%), they were less frequently employed (21.7% versus 27.8%), and more were reliant on social pension (59.2% versus 51.8%). This group also had higher rates of divorce (17.1% versus 16.3%) and widowhood (17.9% versus 15.7%), along with a greater proportion having a CCI > 0 (42.2% versus 36.9%).

For the analysis of readmissions, the patients were categorized into one of the following 20 patient groups according to their main diagnosis or surgical procedure received. Table 5 presents the distribution of patients in the selected patient groups.

Patients with other diseases of the circulatory, respiratory, and gastrointestinal system represented the predominant patient groups, whereas myocardial infarction and colorectal resections constituted the smallest patient groups.

3.3 Burden of Readmissions Post-Discharge

Figure 1 shows the 1-, 2-, 3-, 7-, and 30-day readmission rates for each of the 20 patient groups.

Colorectal resection, heart surgery, myocardial infarction, and patients with cancer were the patient groups with the highest accumulated readmission rates, all above 10%. Table 6 shows the exact estimates of readmission rates, average LOS, and costs of 3-day and 30-day readmissions for each patient group. Estimates for the 1-, 2-, and 7-day readmissions are provided in Online Resource 1 (Tables S3–S5).

The overall readmission rate was 1.7% for readmissions within 3 days and 7.5% for readmissions within 30 days of discharge. Generally, the readmission rates were similar between medical and surgical patients. Patients with myocardial infarction had the highest 3-day readmission rate (4.4%) and a notably high 30-day readmission rate (11.2%). Similarly, patients undergoing colorectal resection demonstrated a substantial 3-day readmission rate (3.2%) and the highest 30-day readmission rate across all groups (11.8%). Patients who underwent heart surgery also showed elevated readmission rates, with 2.4% at 3 days and 11.3% at 30 days. In contrast, patients undergoing hip and knee replacement, as well as other orthopedic surgeries, had relatively low readmission rates for both 3-day (1.1% for hip and knee replacement, and 0.7% for other orthopedic procedures) and 30-day readmissions (5.4% for hip and knee replacement, and 3.4% for other orthopedic surgery). In addition, patients who underwent surgery on female reproductive organs had among the lowest readmission rates across both time frames (1.1% and 4.2%).

The average overall LOS was 4.4 days for 3-day readmissions and 4.2 days for 30-day readmissions, and the corresponding average costs were EUR 4674 and EUR 4955, respectively. For 3-day readmissions, myocardial infarction patients had the longest stays (9.3 days), followed by patients with cancer (6.2 days) and colorectal surgery patients (6.1 days). For 30-day readmissions, cancer, vascular, and

[2] See detailed calculation in Table S1 in Online Resource 1.

Table 2 Cost items and values in the cost estimation for each scenario

Cost items	Scenario 1 (base case)	Scenario 2 (low-cost)	Scenario 3 (high-cost)	Source
Price of WARD-CSS				
List price of WARD-CSS	4027 EUR	4027 EUR	4027 EUR	HumanBytes
Costs of monitoring devices	5359 EUR	5359 EUR	5359 EUR	HumanBytes
Server for data storage	268 EUR	268 EUR	268 EUR	Assumption
Total upfront costs	9376 EUR	9376 EUR	9376 EUR	Calculation
Estimated life span	3 years	3 years	3 years	Assumption
Annual depreciation	3125 EUR	3125 EUR	3125 EUR	Calculation
Monitoring period	3 days	3 days	3 days	WARD-Home [16]
Production days per year	300 days	300 days	300 days	HumanBytes
Capacity per year	100 patients	100 patients	100 patients	HumanBytes
Initial costs per patient per year (non-depreciated)	97 EUR	97 EUR	97 EUR	Calculation (see Online Resource 1, Table S1)
Costs per patient per year (depreciation-based)	32 EUR	32 EUR	32 EUR	Calculation (see Online Resource 1, Table S1)
Monitoring process: time estimates and alarm frequency (per patient)				
Time for installation by hospital nurse	8 min	8 min	8 min	Sigvardt et al. [19]
Time for instruction by hospital nurse	15 min	0 min	30 min	WARD-Home project team
Number of alarms	8	2	14	WARD-Home project team
Time for handling first alarm by hospital nurse	7 min	7 min	7 min	Interview with nurse
Time for handling subsequent alarms by hospital nurse	3.5 min	3.5 min	3.5 min	WARD-Home project team
Number of alarms requiring additional evaluation	1	0	2	WARD-Home project team
Time for additional evaluation—phone call by hospital nurse	13 min	13 min	13 min	Interview with nurse
Time for removal of monitoring devices in the patient's home by hospital nurse	30 min	30 min	30 min	WARD-Home project team
Rates and costs				
Average time cost (hospital nurse)	62 EUR	62 EUR	62 EUR	The Danish Medicines Council [18]
Average transportation cost	19 EUR	19 EUR	19 EUR	The Danish Medicines Council [18]
Cost of clinical evaluation (outpatient visit)	185 EUR	185 EUR	185 EUR	DRG tariff system guide [25]
Transportation to hospital not leading to readmission, proportion of patients	0.0168[a]	0.0084[b]	0.0336[c]	Assumption

WARD-CSS, WARD Clinical Support System; EUR, Euro; Min, minutes; DRG, diagnosis-related group

[a]Assumed to be equal to the 3-day readmission rate derived from registry-based analysis below

[b]Assumed to be half the 3-day readmission rate derived from registry-based analysis below

[c]Assumed to be twice the 3-day readmission rate derived from registry-based analysis below

orthopedic surgeries had the longest stays (5.3–5.5 days). In terms of cost, the most expensive 3-day readmissions were observed in patients with cancer (EUR 6552) and those who underwent respiratory organ surgery (EUR 6341). Similarly, patients with cancer had the highest costs for 30-day readmissions (EUR 6353), along with patients undergoing vascular surgery (EUR 6961).

3.4 Burden of Readmissions following Planned versus Emergency Admissions

Of the 285,930 primary admissions, 110,679 were planned admissions and 175,251 were emergency admissions. The overall 3-day readmission rates following planned and emergency admissions were 1.9% and 1.6%, respectively (results

Table 3 Cost of continuous remote monitoring by WARD-CSS per patient monitored in each scenario

Scenario	Total monitoring cost (EUR)
Scenario 1 (base case)	159
Scenario 2 (low-cost)	109
Scenario 3 (high-cost)	217

presented in Table S6 in Online Resource 1). For 30-day readmissions, the readmission rates were 9.0% for readmissions following planned admissions and 6.5% for readmissions following emergency admissions (results provided in Table S7 in Online Resource 1).

Figure 2 shows the 1-, 2-, 3-, 7-, and 30-day readmission rates following planned and emergency hospital admissions, respectively, for each of the patient groups.

In most groups, the highest 30-day readmission rates were observed following planned admissions, with the exception of endocrine diseases, vascular diseases, and infectious diseases. Patients with myocardial infarction and those undergoing surgery on female reproductive organs exhibited similar 30-day readmission rates after planned and emergency admissions, respectively.

Comparing the average LOS and costs of readmissions following planned and emergency admissions revealed an average LOS of 3-day readmissions of 4.4 days after planned hospital admissions and of 4.3 days after emergency hospital admissions (results provided in Table S6 in Online Resource 1). Average costs of 3-day readmissions were EUR 4839 and EUR 4548 after planned and emergency readmissions, respectively (results provided in Table S6 in Online Resource 1). For the 30-day readmissions, the average LOS was 4.4 after planned admissions and 4.1 after emergency admissions (results provided in Table S7 in Online Resource 1). The average costs of 30-day readmissions were EUR 5245 after planned admissions and EUR 4701 after emergency admissions (results provided in Table S7 in Online Resource 1).

Detailed estimates for 3-day and 30-day readmission rates are provided in Tables S6 and S7 in Online Resource 1, including the number of observations (Table S8 in Online Resource 1).

3.5 Comparing Expected Costs with Potential Savings

The cost estimation demonstrated that 3-day post-discharge home monitoring with WARD-CSS incurred costs of EUR 159 per patient. In addition, the registry-based analysis showed that the average readmission cost within a comparable 3-day period was EUR 4674. Comparing these two estimates shows that the cost of one readmission is equivalent to the costs of monitoring 29 patients. This indicates that cost-neutrality could be achieved if one readmission is prevented for every 29 patients monitored. In the low-cost scenario, cost-neutrality would be achieved by preventing one readmission for every 43 patients, while in the high-cost scenario, this number decreases to 22. However, the number of patients required to achieve cost-neutrality varies by the target population. For instance, among patients with cancer, WARD-CSS achieves cost-neutrality if one readmission is prevented for every 41 patients monitored (base case scenario). Conversely, in patients undergoing surgery on female reproductive organs, WARD-CSS needs to prevent one readmission for every 19 patients to break even (base case scenario). Regardless of the scenario or target group, the cost of WARD-CSS for remote monitoring for 3 days is significantly lower than the cost of a 3-day readmission. This suggests that, if the intervention proves effective in reducing readmissions, only a modest reduction would be required to achieve cost neutrality—provided that no additional healthcare costs are incurred outside the hospital or beyond the 3-day post-discharge period.

4 Discussion

In this study, we utilized the WARD-CSS as a concrete example of a monitoring technology to estimate the cost of continuous remote monitoring in the post-discharge home setting. Moreover, we examined the potential for such an intervention to reduce readmissions among various patient groups by estimating the burden of readmissions in terms of frequency, average LOS, and costs. The per-patient cost of WARD-CSS over a 3-day monitoring period was EUR 159 in the base case scenario, ranging from EUR 109 in the low-cost scenario to EUR 217 in the high-cost scenario. In addition, we found readmission rates of 1.7% for 3-day readmissions and 7.5% for 30-day readmissions across all groups. Comparing the expected costs associated with WARD-CSS for post-discharge home use and the average costs of readmissions indicates that preventing just one readmission within 3 days in every 29 patients monitored is sufficient to achieve cost-neutrality. This conclusion, however, assumes that post-discharge monitoring both effectively reduces readmissions and does not lead to increased healthcare costs in non-hospital settings.

By basing our cost estimation on a specific technology—WARD-CSS—and a defined monitoring approach from the WARD-Home study, we provide a concrete and contextually relevant analysis of continuous remote monitoring and its associated costs. However, this also means that the cost estimates used in the cost estimation are specific to the conditions of the WARD-Home study and may not fully represent

Table 4 Baseline characteristics of patients not readmitted, patients readmitted within 3 days, and patients readmitted within 30 days, respectively

	No readmission (*n*)	%	3-day readmission (*n*)	%	30-day readmission (*n*)	%
n	264,628	92.5	4816	1.7	21,302	7.5
Mean age at primary admission	64.0		64.5		66.7	
Age groups						
18–39 years	29,122	11.0	546	11.3	1666	7.8
40–59 years	60,564	22.9	1004	20.8	4158	19.5
60–79 years	127,153	48.0	2321	48.2	10,824	50.8
80 + years	47,789	18.1	945	19.6	4654	21.8
Sex						
Male	131,061	49.5	2506	52.0	11,082	52.0
Female	133,567	50.5	2310	48.0	10,220	48.0
Highest level of education						
Primary school	95,981	36.3	1725	35.8	8145	38.2
General upper secondary education	8766	3.3	177	3.7	627	2.9
Vocational upper secondary education	2648	1.0	48	1.0	189	0.9
Vocational education and training	98,561	37.2	1793	37.2	7905	37.1
Short higher education	8248	3.1	158	3.3	712	3.3
Medium higher education	33,277	12.6	589	12.2	2455	11.5
Bachelor degree	2233	0.8	33	0.7	119	0.6
Long higher education	14,144	5.3	277	5.8	1088	5.1
PhD	770	0.3	16	0.3	62	0.3
Employment status/social support						
Employed	73,493	27.8	1221	25.4	4613	21.7
In education	6120	2.3	105	2.2	341	1.6
Unemployed	1785	0.7	27	0.6	124	0.6
Sickness benefits/leave/education allowance	2209	0.8	45	0.9	190	0.9
Disability pension	22,477	8.5	402	8.3	1887	8.9
Social pension	137,047	51.8	2650	55.0	12,616	59.2
Early retirement	4694	1.8	70	1.5	336	1.6
Social security benefit	12,663	4.8	219	4.5	917	4.3
Others out of work	4140	1.6	77	1.6	278	1.3
Ethnic origin						
Danish	246,584	93.2	4466	92.7	19,864	93.2
Immigrant	16,184	6.1	308	6.4	1308	6.1
Descendant	1860	0.7	42	0.9	130	0.6
Marital status						
Married	129,410	48.9	2369	49.2	10,449	49.1
Unmarried	50,481	19.1	888	18.4	3393	15.9
Divorced	43,213	16.3	806	16.7	3652	17.1
Widowed	41,524	15.7	753	15.6	3808	17.9
CCI						
CCI 0	166,887	63.1	2900	60.2	12,322	57.8
CCI 1–2	68,869	26.0	1329	27.6	5909	27.7
CCI ≥ 3	28,872	10.9	587	12.2	3071	14.4

CCI, Charlson's Comorbidity Index

Table 5 Distribution of patients in the selected patient groups by decreasing incidence

Patient group	Number of patients	%
Other diseases of the circulatory system	30,038	10.5
Other diseases of the respiratory system	29,763	10.4
Diseases of the gastrointestinal system	28,437	9.9
Other orthopedic surgery	23,502	8.2
Other major abdominal surgery	19,562	6.8
Hip and knee replacement surgery	19,199	6.7
Vascular and infectious diseases of the brain	17,037	6.0
Endocrine diseases	16,305	5.7
Diseases of the genitourinary system	15,539	5.4
Cancer	15,200	5.3
Infectious diseases	14,645	5.1
Surgery on genitourinary system	10,490	3.7
Intracranial surgery	7485	2.6
Heart surgery	6894	2.4
Surgery on respiratory organs	6546	2.3
Vascular surgery	6660	2.3
AECOPD	6426	2.2
Surgery on female reproductive organs	5825	2.0
Colorectal resections	3929	1.4
Myocardial infarction	2448	0.9
Total	285,930	100

AECOPD, chronic obstructive pulmonary disease (COPD) with either acute exacerbation or acute lower respiratory infection

future applications of WARD-CSS or similar monitoring technologies. The average monitoring period used in our analysis was 3 days, in line with the WARD-Home study, but in practice, the monitoring period could be extended. Consequently, while our analysis is based on 3-day readmission rates and costs, we acknowledge that WARD-CSS or similar technologies may also prevent complications that could lead to readmissions beyond the 3-day monitoring period. Furthermore, transportation costs and time cost of a nurse are average values derived from guidelines for cost analyses of pharmaceuticals used in assessments by the Danish Medicines Council and may not reflect real-world variations or site-specific conditions. There are significant differences in nurse salaries internationally, with Denmark ranking among the highest [26]. Consequently, the time cost of a nurse—and therefore the total monitoring cost—would be lower if post-discharge monitoring was implemented in a country with lower salaries such as Portugal. Regarding transportation costs, Denmark's relatively small size implies shorter travel distances, which likely result in lower transportation costs compared with countries with larger geographical areas.

Besides being context-dependent, the cost estimation is also surrounded by a lot of uncertainty owing to several factors. Although the list price of the system includes onboarding of healthcare staff, the estimation does not account for future training of new personnel. The costs of the monitoring devices may vary on the basis of the provider and the specific devices required, and the costs of server installation depends on the hospital ward's need. The number of alarms during the monitoring period represents an average across patients with diverse risk profiles. Consequently, monitoring costs will be higher for high-risk patients with more frequent alarms, and lower for low-risk patients with fewer alarms. The primary cost drivers are the time required for handling alarms and removing the devices at the end of the monitoring period. To reduce these costs, it would be necessary to lower the frequency of alarms or decrease the time required to manage them, as well as streamline the removal process if possible. As the system undergoes continuous

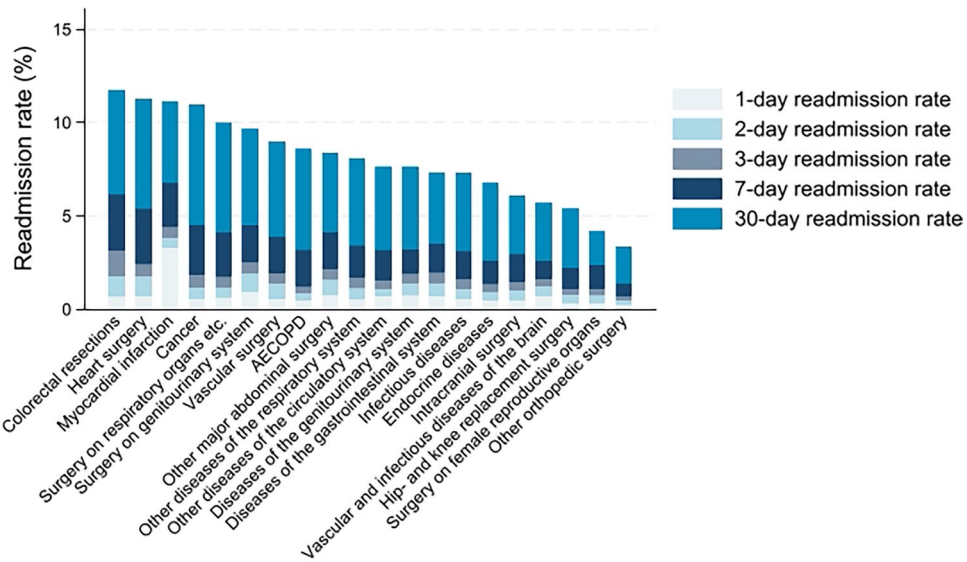


Fig. 1 Readmission rates for each patient group. AECOPD, chronic obstructive pulmonary disease (COPD) with either acute exacerbation or acute lower respiratory infection

Table 6 Readmission rates, average LOS, and cost of readmissions within 3 and 30 days

Patient group	Readmitted within 3 days				Readmitted within 30 days			
	Readmitted patients (n)	Readmission rate (%)	Avg. LOS (days)	Avg. cost (EUR)	Readmitted patients (*n*)	Readmission rate (%)	Avg. LOS (days)	Avg. cost (EUR)
Colorectal resections	125	3.18	6.1	5732.40	462	11.76	4.7	4918.27
Heart surgery	167	2.42	3.9	3514.34	777	11.27	4.2	3709.79
Myocardial infarction	108	4.41	9.3	4917.53	273	11.15	5.0	4166.51
Cancer	282	1.86	6.2	6552.32	1667	10.97	5.3	6353.13
Surgery on respiratory organs, etc.	114	1.74	4.8	6341.18	656	10.02	4.5	5308.84
Surgery on genitourinary system	264	2.52	3.1	4312.21	1015	9.68	3.8	4479.04
Vascular surgery	129	1.94	4.6	5775.81	597	8.96	5.5	6961.20
AECOPD	78	1.21	3.9	5523.80	552	8.59	3.7	4649.18
Other major abdominal surgery	424	2.17	4.1	4351.53	1640	8.38	4.1	4418.98
Other diseases of the respiratory system	514	1.73	3.5	4815.04	2410	8.10	4.0	5009.27
Other diseases of the circulatory system	470	1.56	5.9	4458.72	2301	7.66	4.3	4961.61
Diseases of the genitourinary system	296	1.90	3.3	3646.46	1190	7.66	3.5	4470.20
Diseases of the gastrointestinal system	560	1.97	3.6	4215.21	2087	7.34	3.9	4820.17
Infectious diseases	239	1.63	4.2	4746.77	1071	7.31	4.4	4948.36
Endocrine diseases	221	1.36	4.2	4027.54	1108	6.80	4.0	4471.63
Intracranial surgery	109	1.46	5.0	5975.05	455	6.08	4.7	6056.23
Vascular and infectious diseases of the brain	276	1.62	3.5	5858.64	971	5.70	3.4	4848.68
Hip and knee replacement surgery	212	1.10	4.3	3380.95	1034	5.39	4.5	5058.32
Surgery on female reproductive organs	65	1.12	2.6	3009.89	244	4.19	3.2	3019.42
Other orthopedic surgery	163	0.69	4.7	4583.05	792	3.37	5.3	5257.50
Total	4816	1.68	4.4	4673.68	21,302	7.45	4.2	4955.34

AECOPD, chronic obstructive pulmonary disease (COPD) with either acute exacerbation or acute lower respiratory infection

improvements, it is anticipated that alarm frequency could be reduced.

The cost estimation did not consider monitoring in combination with other treatments in the home, resource use in other sectors, or informal care, as these data were unavailable. Following discharge, patients remain under the clinical oversight of the hospital ward from which they were discharged and are advised to contact the ward staff directly if any issues arise during the subsequent 3-day monitoring period. Although patients retain the option to consult their general practitioner or access sub-acute emergency services during this time, a substantial increase in such utilization is not anticipated, given the limited duration of the monitoring interval. However, owing to a lack of data, no conclusions can be drawn regarding potential costs in other sectors. It is essential to ensure that the implementation of post-discharge monitoring does not inadvertently transfer the burden of care to primary healthcare services. In addition, assessing the impact on informal caregivers is crucial to fully understand the broader implications and sustainability of this approach.

Another limitation of this study is the absence of outcome data, which precludes a full economic evaluation. Since the WARD-Home study did not include outcome data for the current analysis, the impact of post-discharge monitoring on readmission rates or additional outcomes remains unknown. Consequently, the comparison between costs of post-discharge home monitoring and current readmission costs do not account for potential differences in any outcomes between monitored and non-monitored patients. Although post-discharge monitoring is anticipated to reduce

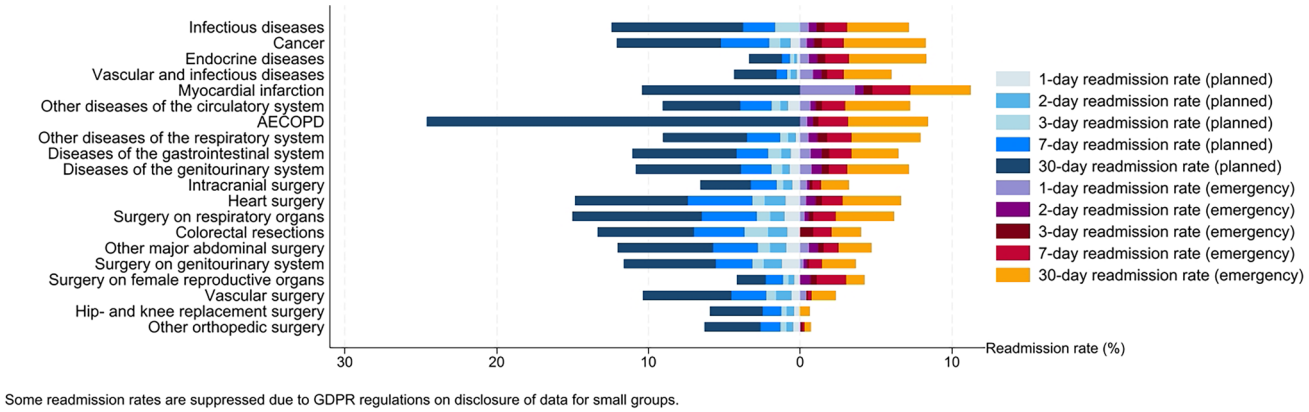


Fig. 2 Readmission rates following planned and emergency hospital admission, respectively, for each patient group. AECOPD, chronic obstructive pulmonary disease (COPD) with either acute exacerbation or acute lower respiratory infection

readmissions, there remains a possibility that this may not be achieved. Moreover, the likelihood that post-discharge home monitoring will offset associated costs may vary between patient groups. For instance, the high readmission rates observed among colorectal resection patients may be driven by postoperative complications that are less amenable to prevention through monitoring alone. However, by enabling early detection, these readmissions may occur sooner but with reduced severity. The net effect of these dynamics on healthcare costs, however, remains uncertain.

Given the absence of outcome data and the omission of certain cost components in the cost estimation, the findings of this study should be regarded as preliminary and interpreted with caution. A comprehensive evaluation of the economic impact and potential cost-effectiveness of post-discharge monitoring necessitates the inclusion of all relevant cost components and an assessment of its real-world effects on patient outcomes, particularly its impact on readmission rates.

That said, even if monitoring by WARD-CSS in the post-discharge home setting does not directly reduce readmission rates, it may offer other significant benefits. For instance, the intervention could reduce patient mortality or decrease overall LOS, as early detection and expedited readmissions may lower the severity of patients' conditions. These are key outcomes that warrant investigation. Furthermore, admitting patients to their homes for monitoring could allow hospitals to better allocate resources, focusing care on those in greater need. From the patient's perspective, being cared for in their own home may offer various advantages, such as staying in familiar surroundings, being close to family, and maintaining aspects of their daily routine.

The integration of novel technologies such as continuous remote monitoring is not without its challenges and potential drawbacks. False alarms or misinterpretation of data can lead to unnecessary hospital visits, while over-reliance on technology may result in increased vigilance for both patients and healthcare staff. Alarm fatigue can occur when frequent alerts lead to desensitization, potentially resulting in undetected deterioration [27]. Therefore, it is crucial to ensure that data from continuous remote monitoring systems are accurately interpreted to minimize unnecessary interventions while still allowing timely responses to clinically relevant outcomes.

A strength of the analysis of readmissions is the use of high-quality registry data, which enables a comprehensive and reliable analysis. To estimate readmissions costs, we relied on DRG tariffs, representing average treatment costs of specific DRG groups. While DRG tariffs are commonly used as proxies for hospital costs, they do not permit precise allocation of costs within individual admissions. Access to detailed cost data would have enabled a more granular breakdown of readmission costs; however, such data were not available.

Comparing the readmission rates observed in our analysis with those reported in literature reveals both differences and similarities. Shorten et al. [28] found a readmission rate of 10.7% within 40 days after colorectal surgery, comparable to our observed rate of 11.76%. Similarly, Rao et al. (2023) reported a 30-day readmission rate of 8.68% after open-heart surgery [29], while our study reported a slightly higher rate of 11.27%. Shawon et al. [30] analyzed readmission rates for cardiac surgery and found a readmission rate of 14.7% within 30 days. This rate is higher than our estimate of 11.27%; however, our study encompasses a broader range of heart procedures. In addition, Wang et al. [31] reported a pooled 30-day readmission rate of 12% after acute myocardial infarctions across 14 studies, aligning closely to our

finding of 11.5%. García-Tirado et al. [32] found lung resection readmission rates ranging between 4.3 and 15%, also consistent with our estimate of 10.02%. One notable disparity arises in the case of patients with (AE)COPD. Ruan et al. [33] reported an all-cause readmission rate of 18% within 30 days for patients with COPD, on the basis of 27 studies, which is considerably higher than our estimate of 8.6%. The differences between our estimates and those in literature may be attributed to variations in the definitions of patient and disease groups, including whether classifications are based on primary diagnoses alone or include secondary diagnoses. Identifying literature that employs the exact same categorization of patients can be challenging. Discrepancies may also stem from differing data sources and methodologies employed, making direct comparisons challenging.

HaH models, which either aim to expedite discharge (early supported discharge) or avoid hospital admission altogether (admission avoidance), present a promising alternative to traditional in-hospital care. One key challenge, however, is identifying which patients would benefit most from home admission, including continuous remote monitoring. It is essential to ensure that those who will benefit most from home-based care are properly identified and supported. In this study, we have analyzed the burden of specific patient groups to identify which groups are most relevant for monitoring on the basis of their potential for reducing readmissions. However, the selection process for home-based admission or monitoring should not necessarily be strictly limited to medical conditions, as in this study; it may also consider factors such as social circumstances, digital literacy, and support systems at home. While some diseases or surgeries may make patients strong candidates, their social situation and ability to interact with technology are also critical for the intervention's success.

Finally, as HaH models gain broader adoption, it is increasingly important to establish reimbursement mechanisms aligned with their unique care delivery characteristics. Internationally, reimbursement structures vary, with some systems providing full coverage while others incorporate patient cost-sharing components [34]. In the USA, the fee-for-service payment model has limited the widespread implementation of HaH programs; by reducing dependency on facility-based care, HaH models disrupt traditional financial incentives and, thus, face resistance in uptake [35, 36]. Alternative models, such as bundled payment models or similar episode-based reimbursement models may better support HaH models by aligning incentives and enhancing care coordination [35]. These considerations underscore the importance of careful policy design to ensure the sustainable and equitable expansion of HaH models.

5 Conclusions

This study estimated the per-patient costs of WARD-CSS post-discharge home monitoring over a 3-day monitoring period, which was EUR 159 in the base case scenario. Moreover, the study identified average readmission rates of 1.7% and 7.5% at 3- and 30-day post-discharge across 20 patient groups, with average readmission costs of EUR 4674 and EUR 4955, respectively. Cost-neutrality could be achieved if post-discharge home monitoring successfully prevents one readmission in every 29 patients monitored. However, as the study does not include all potentially relevant post-discharge costs and lacks outcome data, further studies are required to establish the full costs and benefits of post-discharge home monitoring before definitive conclusions regarding cost-neutrality or potential savings can be drawn.

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Declarations

Competing interests CSM and EKA have founded WARD24/7 ApS, Copenhagen, Denmark, with the aim of pursuing the regulatory and commercial activities of the WARD-project (developing a clinical support system for continuous wireless monitoring of vital signs). WARD24/7 ApS has signed a license agreement for any WARD-project software and patents. One patent has been filed: "Wireless Assessment of Respiratory and circulatory Distress (WARD), EP 21184712.4 and EP 21205557.8". ATL, LS, SRK, and JK declare no competing interests.

Author contributions All authors have read and approved the final manuscript and agree to be accountable for the integrity and accuracy of the work. Arendse Tange Larsen contributed to the concept and design of the study, performed the interviews, conducted all data management and statistical analyses, prepared figures and tables, drafted the manuscript, and critically revised the manuscript. Liza Sopina contributed to the concept and design of the paper and interpretation of data and provided critical revisions to the manuscript. Eske Kvanner Aasvang contributed to the concept and design of the study, and acquisition of data, as well as provided critical revisions to the manuscript, secured funding, and provided overall supervision of the project. Christian S. Meyhoff contributed to the concept and design of the study and acquisition of data, as well as provided critical revisions to the manuscript, secured funding, and provided overall supervision

of the project. Søren Rud Kristensen contributed to the concept and design of the study, acquisition of registry data, interpretation of data, and drafting the manuscript, as well as provided critical revisions and supervision of the project. Jakob Kjellberg contributed to the concept and design of the paper, acquisition of data, interpretation of data, and provided critical revisions and overall supervision of the project.

Data availability statement The data used for the registry-based analysis is not openly available owing to regulations set by Statistics Denmark, as it includes individual patient-level information. However, all data used for the cost estimation is provided within the manuscript and supplementary material.

Ethics approval Not applicable.

Code availability Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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