



Cost-Effectiveness of Remote Cardiac Monitoring With the CardioMEMS Heart Failure System: A Systematic Review

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Abstract

Background: Heart Failure (HF) imposes a relevant burden and a considerable health concern, with high prevalence and mortality rates. This study was conducted to assess the cost-effectiveness of remote cardiac monitoring with the CardioMEMS Heart Failure System.

Methods: In the present systematic review, several scholarly databases were searched and updated from inception up to September 20, 2022. The objective of the present review was formulated according to the patient/population, intervention, comparison and outcomes format. Mortality rate, hospitalization rate, quality-adjusted life year (QALY), total costs, and the incremental cost-effectiveness ratio regarding the use of the CardioMEMS System were the key outcomes of the present study. The quality of included studies was assessed using the Consolidated Health Economic Evaluation Reporting Standards 2022 (CHEERS) checklist.

Results: Finally, 5 articles were retained and analyzed in the present systematic review. All studies employed the Markov and decision tree models. Results show that the CardioMEMS system reduced mortality and hospitalization rate and created a higher QALY. In all selected countries the CardioMEMS method is a more expensive method than the standard of care (SoC), with the highest cost in the United States (US) (\$201,437) and the lowest cost in the United Kingdom (\$25,963), respectively. The highest willingness to pay in the US and the lowest in Italy (\$100,000 and \$33,000 per QALY), respectively. Results showed that the most cost per QALY for the CardioMEMS system was in the US and the lowest was in the Netherlands (\$46,622 and \$26,615 per QALY), respectively.

Conclusion: In all selected countries, CardioMEMS is a cost-effective method for monitoring and managing pulmonary artery pressures in HF patients. Strategies such as CardioMEMS, which decrease the rate of hospitalization, are likely to be only more cost-effective in the future.

Keywords: CardioMEMS System, Heart Failure, Pulmonary Artery Pressures, Cost-Effectiveness, Systematic Review

Conflicts of Interest: None declared

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Introduction

Heart failure (HF) is a complex clinical syndrome caused by either functional or structural impairment of ventricles

resulting in symptomatic left ventricle (LV) dysfunction (1). From a clinical perspective, HF is mainly characterized

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↑What is “already known” in this topic:

The steady increase of HF prevalence worldwide, coupled with the aging population, is associated with significant mortality, morbidity, and health care expenditures, and the pressure on health care payers to reduce hospitalizations will continue unabated. The purpose of pulmonary artery pressure (PAP) monitoring via the CardioMEMS System was to reduce HF hospitalizations and mortality rates and improve health outcomes.

→What this article adds:

The results of this study showed that CardioMEMS is a cost-effective method for monitoring and managing PAP in HF patients. Strategies such as CardioMEMS, which decrease the rate of hospitalization, are likely to be only more cost-effective in the future.

by symptoms such as dyspnea, fatigue, and fluid retention. From an epidemiological standpoint, HF imposes a relevant burden and a considerable health concern, with high prevalence and mortality rates. It has been estimated that there were over 37.7 million HF cases worldwide in 2016, and this number is expected to increase continuously during the next decades (1-3). The steady increase of HF prevalence worldwide, coupled with the aging population, is associated with significant mortality, morbidity, and health care expenditures and the pressure on health care payers to reduce hospitalizations will continue unabated (4-6).

Pulmonary hypertension (PH) is defined as a mean pulmonary arterial pressure (PAP) ≥ 25 mm Hg measured by right heart catheterization (7, 8). Remote monitoring of intracardiac and PAPs in patients with HF using implantable hemodynamic monitoring devices can provide physicians with access to actionable pathophysiological information and help improve the HF management decision-making process necessary to prevent HF hospitalizations (6, 9, 10). A novel wireless PAP measurement system (CardioMEMS HF System) was evaluated in the CardioMEMS Heart Sensor Allows Monitoring of Pressure to Improve Outcomes in New York Heart Association functional Class III HF Patients (CHAMPION) trial in high-risk symptomatic patients, regardless of ejection fraction (11-13). The purpose of PAP monitoring via the CardioMEMS system was to reduce HF hospitalizations and mortality rates and improve health outcomes such as quality-adjusted life years (QALYs) (6, 14, 15). The CardioMEMS device has been approved for patients with HF with preserved ejection fraction (HFpEF) and HF with reduced ejection fraction (HFrEF) by the US Food and Drug Administration in 2014, and in June 2016 the Heart Failure Association of the European Society of Cardiology (ESC) included the system in the ESC guidelines for diagnosis and treatment of acute and chronic HF (16, 17).

HF poses a major public health burden globally. The cost of HF is catastrophic and causes a significant burden on global health care systems. With the assumption of the continuation of present care practices, a marked increase in health care costs is expected due to the longer survival and consequent increase in the aging population (16, 18, 19). The cost of HF management is projected to increase markedly: a 2.5-fold increase from US\$ 20.9 billion in 2012 to US\$ 53.1 billion by 2030. Of note, 80% of the costs are related to HF hospitalizations. The total cost, including indirect costs, is estimated to increase from US\$ 31 billion in 2012 to US\$ 70 billion by 2030. The estimated average cost for patients with HF during the final 2 years of life is more than US\$ 156,000, and 75% of this cost is attributed to HF-related hospital admissions during the last 6 months of life (16, 20).

Thus, from a societal policy perspective, a critical health care goal should be to achieve the best possible health outcomes with finite health care resources (21, 22). Given the limited global health care budget, evidence-based studies and economic appraisals need to support health care decisions and policymakers to achieve the best value (health benefit for every spent) and resource allocation. Within this context, to our knowledge, this is the first systematic review of the CardioMEMS system, aimed at systematically collect and synthesize available economic evaluation studies to investigate the possibility of cost-effectiveness and the impact of remote cardiac monitoring with the CardioMEMS system in main health outcomes in HF patients.

Methods

The objective of the present review was formulated according to the patient/population, intervention, comparison and outcomes format. In addition, inclusion and exclusion criteria were determined as well (Table 1).

Published full-economic evaluations and appraisals of the CardioMEMS wireless monitoring system for HF patients were included in the review. Studies comparing the cost-effectiveness of the CardioMEMS wireless monitoring system versus Soc were deemed eligible. Several scholarly databases were searched, including PubMed/MEDLINE, Embase, Web of Science, National Health Service Economic Evaluation Database, Database of Abstracts of Reviews of Effects (DARE), Health Technology Assessment Database, Scopus, the Cochrane Library, the Tufts Medical Center Cost-Effectiveness Analysis Registry, the Institute for Clinical and Economic Review (ICER), and the National Institute for Health and Care Excellence. Databases were searched on June 1, 2021, and updated from inception up to September 20, 2022. To obtain relevant studies, the reference list of included studies was also scanned. The adopted search strategy in 3 main databases is reported in Table 2.

Main Outcomes

Mortality rate, hospitalization rate, quality-adjusted life year (QALY), life-years gained, total costs, and the ICER regarding the use of CardioMEMS were the key outcomes of the present study.

Inclusion and Exclusion Criteria

Studies were included if they (1) investigated the use of CardioMEMS in HF patients; (2) utilized economic evaluations models (such as the Markov model, and decision tree); (3) reported costs, QALY, and ICER; and (4) were published in English. Studies were excluded if they (1) were designed as case reports or case series; (2) were not

Table 1. PICO questions

P	HF patients
I	Remote Cardiac Monitoring with the CardioMEMS
C	Standard of Care treatment
O	Mortality and hospitalization rate, Quality-adjusted life year (QALYs), life years gained (LYG), Total costs and incremental cost-effectiveness ratio (ICER).

Table 2. Complete search strategy for PubMed/MEDLINE, Scopus and Web of Science

Database	Search Strategy
PubMed	("Cost Benefit Analysis"[MeSH Terms] OR "Cost-Benefit Analyses"[Title/Abstract] OR "Cost Effectiveness"[Title/Abstract] OR "Cost Benefit Data"[Title/Abstract] OR "Cost Utility Analysis"[Title/Abstract] OR "Cost-Utility Analyses"[Title/Abstract] OR "Economic Evaluation"[Title/Abstract] OR "Economic Evaluations"[Title/Abstract] OR "Marginal Analysis"[Title/Abstract] OR "Marginal Analyses"[Title/Abstract] OR "Cost Effectiveness Analysis"[Title/Abstract]) AND ("Wireless pulmonary artery haemodynamic monitoring"[Title/Abstract] OR "Wireless pulmonary artery pressure monitoring"[Title/Abstract] OR "pulmonary artery pressure"[Title/Abstract] OR "Heart failure"[MeSH Terms] OR "Heart failure"[Title/Abstract])
Scopus	TITLE-ABS-KEY ("Cost Benefit Analysis" OR "Cost-Benefit Analyses" OR "Cost Effectiveness" OR "Cost Benefit Data" OR "Cost Utility Analysis" OR "Cost-Utility Analyses" OR "Economic Evaluation" OR "Economic Evaluations" OR "Marginal Analysis" OR "Marginal Analyses" OR "Cost Effectiveness Analysis") AND TITLE-ABS-KEY ("Wireless pulmonary artery haemodynamic monitoring" OR "Wireless pulmonary artery pressure monitoring" OR "pulmonary artery pressure" OR "Heart failure")
Web of Science	TS= ("Cost Benefit Analysis" OR "Cost-Benefit Analyses" OR "Cost Effectiveness" OR "Cost Benefit Data" OR "Cost Utility Analysis" OR "Cost-Utility Analyses" OR "Economic Evaluation" OR "Economic Evaluations" OR "Marginal Analysis" OR "Marginal Analyses" OR "Cost Effectiveness Analysis") AND TS= ("Wireless pulmonary artery haemodynamic monitoring" OR "Wireless pulmonary artery pressure monitoring" OR "pulmonary artery pressure" OR "Heart failure")

full-text peer-reviewed articles, but conference abstracts; and (3) lacked sufficient details or did not report QALY and ICER.

Quality Assessment of the Studies

Two authors independently evaluated the articles according to the Consolidated Health Economic Evaluation Reporting Standards (CHEERS) checklist to assess the methodological quality of the selected studies. Studies that had at least 15 items out of 24 items for the CHEERS checklist were considered acceptable. Any disagreement between the 2 authors was resolved through the involvement of a third author who acted as the final referee (Table 3).

Data Extraction

A standardized data collection sheet was used to extract the data from the included studies. This form had information on general characteristics and main health outcomes. After selecting the studies, 2 authors independently extracted relevant information, including the study/ publication year, country, funding, comparators, perspective, time horizon, number of patients, sensitivity analysis, discount rate, currency, and base year—including costs, patient population, type of modeling, mortality and survival rate, hospitalization rate, QALYs, LYQs, cost, ICER, threshold, and base case results analyzed in each included study. Screening and selection steps were performed independently by 2 researchers. Disagreements were discussed to reach a final decision.

Qualitatively Synthesis of Results

The key characteristics and results of included studies were summarized and synthesized qualitatively using tables and complemented by a narrative description and comparison of the results among studies. In this study, all costs were calculated according to the USD in 2020, and all costs and outcomes were adjusted. This study was conducted and reported in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (23).

Results

The initial search yielded a pool of 730 items, which was reduced to 480 after removing duplicate articles. A subset of 495 articles were discarded by reviewing their titles and/or abstracts and 40 papers were excluded after full-text assessment for eligibility. Finally, 5 articles were retained and analyzed in the present systematic review (Figure 1).

The main characteristics of the included cost-effectiveness studies are shown in Table 4. Table 5 summarizes the health outcomes and cost-effectiveness indices—such as mortality and hospitalization rate, QALYs, LYQs, and cost—and other related economic evaluation parameters for each study. Of the studies, 4 were conducted in the United States (6, 15, 24, 25) and 1 in the UK (17). The perspective of the entered studies is generally from the perspective of the payer and the health care system, and Schmier et al study perspective of the study is not mentioned. The time horizon for studies was generally 5 years, except for Cowie et al (10 years) and Sandhu et al (lifetime horizon) studies. All studies performed a sensitivity analysis on cost-effectiveness results. The discount rate for health outcomes and costs in all studies is 3% per year, except for a study in the UK where the discount rate is 3.5%. Except for the study by Cowie et al, which utilized the currency units of pounds (£) and euros (€), all studies' currencies used to measure expenses were based on the US dollar (USD).

All studies employed the Markov and decision tree models for measuring the cost-effectiveness of the CardioMEMS Remote Cardiac Monitoring System in HF patients. The clinical effectiveness, such as mortality and hospitalization, were derived from the CHAMPION trial Randomized. Studies show that the CardioMEMS Remote Cardiac Monitoring System reduced mortality (Hazard ratio [HR] reduction in mortality, 0.80) and hospitalization (Hazard ratio reduction in HF hospitalization, 0.78).

Cost-Effectiveness of CardioMEMS System in Heart Failure Patients

Table 3. CHEERS checklist

Section/item	Item No	Recommendation	Cowie, 2017	Martinson, 2017	Schmier, 2017	Sandhu, 2016	Ollendorf, 2015
Title and abstract							
Title	1	Identify the study as an economic evaluation or use more specific terms such as “cost-effectiveness analysis”, and describe the interventions compared.	Y	Y	Y	Y	Y
Abstract	2	Provide a structured summary of objectives, perspective, setting, methods (including study design and inputs), results (including base case and uncertainty analyses), and conclusions.	Y	Y	Y	Y	Y
Introduction							
Background and objectives	3	Provide an explicit statement of the broader context for the study. Present the study question and its relevance for health policy or practice decisions.	Y	Y	Y	Y	Y
Methods							
Target population and subgroups	4	Describe characteristics of the base case population and subgroups analysed, including why they were chosen.	Y	Y	Y	Y	Y
Setting and location	5	State relevant aspects of the system(s) in which the decision(s) need(s) to be made.	Y	Y	Y	Y	Y
Study perspective	6	Describe the perspective of the study and relate this to the costs being evaluated.	Y	Y	N	Y	Y
Comparators	7	Describe the interventions or strategies being compared and state why they were chosen.	Y	Y	Y	Y	Y
Time horizon	8	State the time horizon(s) over which costs and consequences are being evaluated and say why appropriate.	Y	Y	Y	Y	Y
Discount rate	9	Report the choice of discount rate(s) used for costs and outcomes and say why appropriate.	Y	Y	Y	Y	Y
Choice of health outcomes	10	Describe what outcomes were used as the measure(s) of benefit in the evaluation and their relevance for the type of analysis performed.	Y	Y	Y	Y	Y
Measurement of effectiveness							
	11a	Single study-based estimates: Describe fully the design features of the single effectiveness study and why the single study was a sufficient source of clinical effectiveness data.	Y	-	Y	Y	Y
	11b	Synthesis-based estimates: Describe fully the methods used for identification of included studies and synthesis of clinical effectiveness data.	Y	Y	-	Y	Y
Measurement and valuation of preference based outcomes							
Estimating resources and costs	12	If applicable, describe the population and methods used to elicit preferences for outcomes.	Y	Y	Y	Y	-
	13a	Single study-based economic evaluation: Describe approaches used to estimate resource use associated with the alternative interventions. Describe primary or secondary research methods for valuing each resource item in terms of its unit cost. Describe any adjustments made to approximate to opportunity costs.	Y	Y	Y	Y	Y
	13b	Model-based economic evaluation: Describe approaches and data sources used to estimate resource use associated with model health states. Describe primary or secondary research methods for valuing each resource item in terms of its unit cost. Describe any adjustments made to approximate to opportunity costs.	Y	Y	Y	Y	Y
Currency, price date, and conversion	14	Report the dates of the estimated resource quantities and unit costs. Describe methods for adjusting estimated unit costs to the year of reported costs if necessary. Describe methods for converting costs into a common currency base and the exchange rate.	Y	Y	Y	Y	Y
Choice of model	15	Describe and give reasons for the specific type of decision-analytical model used. Providing a figure to show model structure is strongly recommended.	Y	Y	Y	Y	Y
Assumptions	16	Describe all structural or other assumptions underpinning the decision-analytical model.	Y	Y	Y	-	Y

Table 3. Continued

Section/item	Item No	Recommendation	Cowie, 2017	Martinson, 2017	Schmier, 2017	Sandhu, 2016	Ollendorf, 2015
Analytical methods	17	Describe all analytical methods supporting the evaluation. This could include methods for dealing with skewed, missing, or censored data; extrapolation methods; methods for pooling data; approaches to validate or make adjustments (such as half cycle corrections) to a model; and methods for handling population heterogeneity and uncertainty.	-	-	Y	-	Y
Study parameters	18	Report the values, ranges, references, and, if used, probability distributions for all parameters. Report reasons or sources for distributions used to represent uncertainty where appropriate. Providing a table to show the input values is strongly recommended.	Y	Y	-	Y	Y
Incremental costs and outcomes	19	For each intervention, report mean values for the main categories of estimated costs and outcomes of interest, as well as mean differences between the comparator groups. If applicable, report incremental cost-effectiveness ratios.	Y	Y	Y	Y	Y
Characterising uncertainty	20a	Single study-based economic evaluation: Describe the effects of sampling uncertainty for the estimated incremental cost and incremental effectiveness parameters, together with the impact of methodological assumptions (such as discount rate, study perspective).	-	-	Y	Y	Y
	20b	Model-based economic evaluation: Describe the effects on the results of uncertainty for all input parameters, and uncertainty related to the structure of the model and assumptions.	-	-	Y	Y	Y
Characterising heterogeneity	21	If applicable, report differences in costs, outcomes, or cost-effectiveness that can be explained by variations between subgroups of patients with different baseline characteristics or other observed variability in effects that are not reducible by more information.	N	N	Y	Y	Y
Study findings, limitations, generalisability, and current knowledge	22	Summarise key study findings and describe how they support the conclusions reached. Discuss limitations and the generalisability of the findings and how the findings fit with current knowledge.	Y	Y	Y	Y	Y
Source of funding	23	Describe how the study was funded and the role of the funder in the identification, design, conduct, and reporting of the analysis. Describe other non-monetary sources of support.	Y	Y	Y	Y	Y
Conflicts of interest	24	Describe any potential for conflict of interest of study contributors in accordance with journal policy. In the absence of a journal policy, we recommend authors comply with International Committee of Medical Journal Editors recommendations.	Y	Y	N	Y	Y

Table 4. Description of each study analyzed in the review

Study/ Publication year	Country	Funding	Comparators	Health Outcomes	Perspective	Time Horizon	Number of patients	Sensitivity analysis	Discount rate	Currency and base year	Included Costs
Cowie, 2017	UK	St. Jude Medical and Medtronic, Novartis, Pfizer	CardioMEMS HF system vs Usual care	Mortality, survival, hospitalization, QALY and ICER	NHS	10-year	5715 patients	Probabilistic sensitivity analysis (PSA)	3.5%	£ and €	Total costs
Martinson, 2017	US	employees of St. Jude Medical	CardioMEMS HF system vs Control group	Mortality, survival, hospitalization QALY, LYQs and ICER	Payer perspective	5-year	CHAMPION trial Randomized: Treatment group=270 Control group=280	Probabilistic sensitivity analysis (PSA)	3%	\$	Total costs
Schmier, 2017	US	St. Jude Medical	CardioMEMS HF system vs standard of care treatment	Mortality, survival, hospitalization, QALY, and ICER	-	5-year	CHAMPION trial Randomized	Y	3%	\$	Total costs
Sandhu, 2016	US	Department of Veteran Affairs and NIH NIA Career Development Award	CardioMEMS HF system vs standard of care	Mortality, survival, hospitalization, QALY, and ICER	Societal perspective	lifetime horizon	CHAMPION trial Randomized	One-way sensitivity analyses	3%	\$	Total costs
Ollendorf, 2015	US	-	CardioMEMS HF system vs standard of care	Mortality, survival, hospitalization, QALY, and ICER	Third-party health care payer	5-year	CHAMPION trial Randomized	One-way Sensitivity Analyses	3%	\$	Total costs

Table 5. Cost-effectiveness indices of studies

Study/ year	Patient population	Type of modelling	Mortality OR survival Rate	Hospitalization	QALYs	LYQs	Cost	ICER	Threshold	Base case results
Cowie, 2017	Pivotal RCT on US patients	A Markov model	Hazard ratio reduction in mortality=0.8 CardioMEMS=5.17 years Usual care=4.79 years Incremental =0.38 years	Hazard ratio reduction in HF hospitalization=0.67	CardioMEMS=3.14 Usual care=2.57 Incremental=0.57	-	CardioMEMS: UK= £17,104 Netherlands= €27,472 Belgium= €20,582 Italy= €30,483 Germany= €35,468 Usual care: UK= £6,189 Netherlands= €14,831 Belgium= €7,187 Italy= €17,556 Germany= €22,121	UK= £19 274/QALY Netherlands= €22,555 Belgium= €23,899 Italy= €23,064 Germany= €23,814	£20,000–£30,000 per QALY by NICE	The analysis indicates that CardioMEMS wireless monitoring into the management of UK HF patients is likely to be a cost-effective addition to the HF treatment pathway for appropriate patients.
Martinson, 2017	CHAMPION trial Randomized	A Markov model	Hazard ratio reduction in mortality=0.8	Hazard ratio reduction in HF hospitalization=0.67	Treatment group=2.56 Control group=2.16 Incremental=0.40	Treatment group=3.70 Control group=3.47	Treatment group= US\$56,974 Control group= US\$ 52,149 Incremental= US\$4,443	US\$12,262 per QALY	US\$50,000 and US\$100,000 per QALY	Standard economic modeling suggests that CardioMEMS HF System is cost-effective from the US-payer perspective.
Schmier, 2017	CHAMPION trial Randomized	A Markov model	Hazard ratio reduction in mortality=0.8 Survival At the end of the 60-month: CardioMEMS=49.6% SoC=23.8% Incremental=25.8%	Hazard ratio reduction in HF hospitalization=0.78	5-Year: CardioMEMS=2.509 SoC=1.926 Incremental =0.58	-	5-Year: CardioMEMS=\$188,880 SoC=\$162,772 Incremental=\$26,108	\$44,832 per QALY	\$50,000 per QALY	Among eligible patients with HF when compared with SoC, the CardioMEMS HF System was found to be cost-effective.

Table 5. Continued

Study/year	Patient population	Type of modeling	Mortality OR survival Rate	Hospitalization	QALYs	LYQs	Cost	ICER	Threshold	Base case results
Sandhu, 2016	CHAMPION trial Randomized	A Markov model	Survival (Years): CardioMEMS=5.72 Usual Care=5.31 Incremental=0.41	Hazard ratio reduction in HF hospitalization=0.63 hospitalizations per patient: CardioMEMS=2.18 Usual Care=3.12	CardioMEMS =2.74 Usual Care=2.46 Incremental=0.28	-	CardioMEMS=\$176,648 Usual Care=\$156,569 Incremental=\$20,079	\$71,462 per QALY \$48,054 per LYQs	\$100,000 per QALY gained	CardioMEMS device is cost-effective if the trial effectiveness is sustained over long periods.
Ollendorf, 2015	CHAMPION trial cohort of NYHA Class III heart failure patients	A Markov model	Hazard ratio died or had a hospitalization for CHF=0.73	Hazard ratio reduction in HF hospitalization=0.63 hospitalizations per patient: CardioMEMS=2.19 Usual Care=3.18	CardioMEMS =2.74 Usual Care=2.44 Incremental =0.30	CardioMEMS=5.72 Usual Care=5.28 Incremental=0.44	CardioMEMS=\$174,037 Usual Care=\$156,764 Incremental=\$17,274	\$57,933 per QALY	\$50,000/QALY, \$100,000/QALY, and \$150,000/QALY	The findings indicate that CardioMEMS has the potential to provide clinical benefit over standard approaches to CHF management. The primary estimate for the cost-effectiveness of CardioMEMS is approximately \$58,000 per QALY gained at an assumed device price of \$17,750. The cost/QALY findings remained below commonly accepted cost-effectiveness thresholds in a variety of secondary analyses and additional sensitivity analyses.

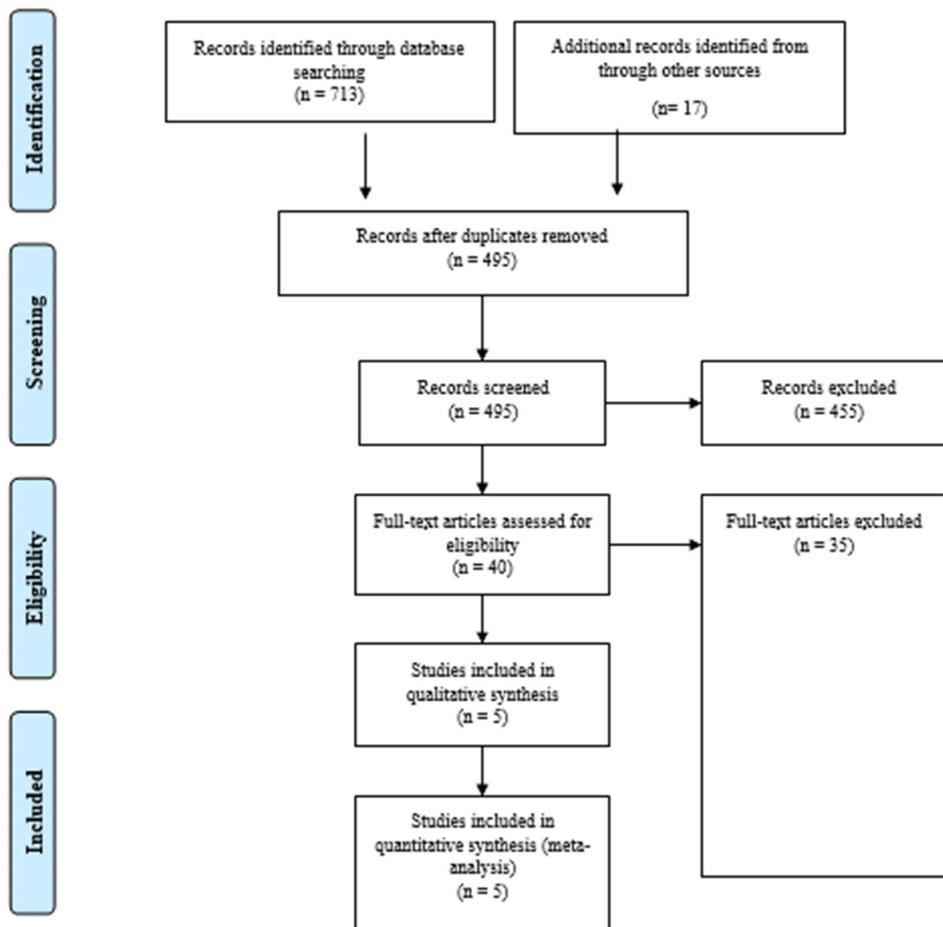


Figure 1. The PRISMA diagram for the identification and selection of studies

Results of all studies indicated that the CardioMEMS system created more QALYs for patients versus SoC. For example, in a study by Cowie et al, the CardioMEMS system and standard therapy created 3.14 and 2.57 QALYs, respectively, and in Martinson et al study, they created 2.56 and 2.16 QALYs, respectively.

Table 5 indicates the total cost over a 5- and 10-year time horizon. The total cost of patient management is the sum of various components for both HF and non-HF management care. The costs associated with hospitalizations for any reason, device- and system-related complications, and remote physiological monitoring were accumulated. In all studies, patients in the CardioMEMS system had the upper cost compared with patients in the control group. For example, in the study of Ollendorf et al in the US health system, the total cost in a 5-year time horizon had \$174,037 for CardioMEMS systems and \$156,764 for SoC. Also, in Cowie et al study, the total cost in a 10-year time horizon from the National Health Service perspective was £17,104(US\$23,603) for patients in the CardioMEMS system and £6,189(US\$8,540) for patients in the control group.

Discussion

To our knowledge, this is the first systematic review of the cost-effectiveness of remote cardiac monitoring with

the CardioMEMS in HF patients. In this review, we aimed to achieve the following:

1. Compare health outcomes such as mortality, hospitalization, and QALY in the CardioMEMS system vs SoC
2. Compare total costs of CardioMEMS vs SoC
3. Discuss the probability of cost-effectiveness of the CardioMEMS monitoring system in HR patients.

Health Outcomes in CardioMEMS System vs SoC

Various factors make therapy cost-effective, and in the case of the CardioMEMS HF system, the cost-effectiveness is attributable to the reduction in HF hospitalization rates, reduction in mortality, and improvement in quality of life. In this systematic review, cost-effectiveness simulation studies formulated input assumptions based on the results from the CHAMPION trial, a multicenter, prospective, randomized controlled US trial that demonstrated a 37% reduction in hospitalizations (Hazard ratio [HR] reduction in HF hospitalization, 0.63) in persistently symptomatic previous HF patients and a 20% reduction of mortality (HR reduction in mortality, 0.8) (9, 12).

QALYs and LYQs indices are important outcome indicators in economic evaluation studies (26), which in the present study are the average of these indicators for entered studies in HF patients in the same direction. The results showed that the CardioMEMS HF system has created

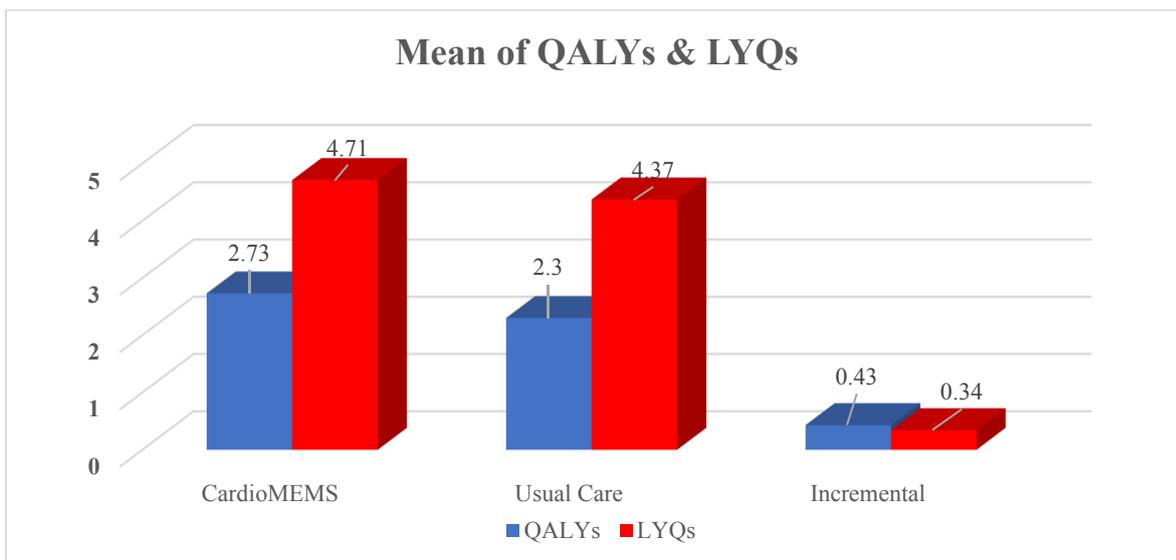


Figure 2. Mean of QALYs and LYQs in studies

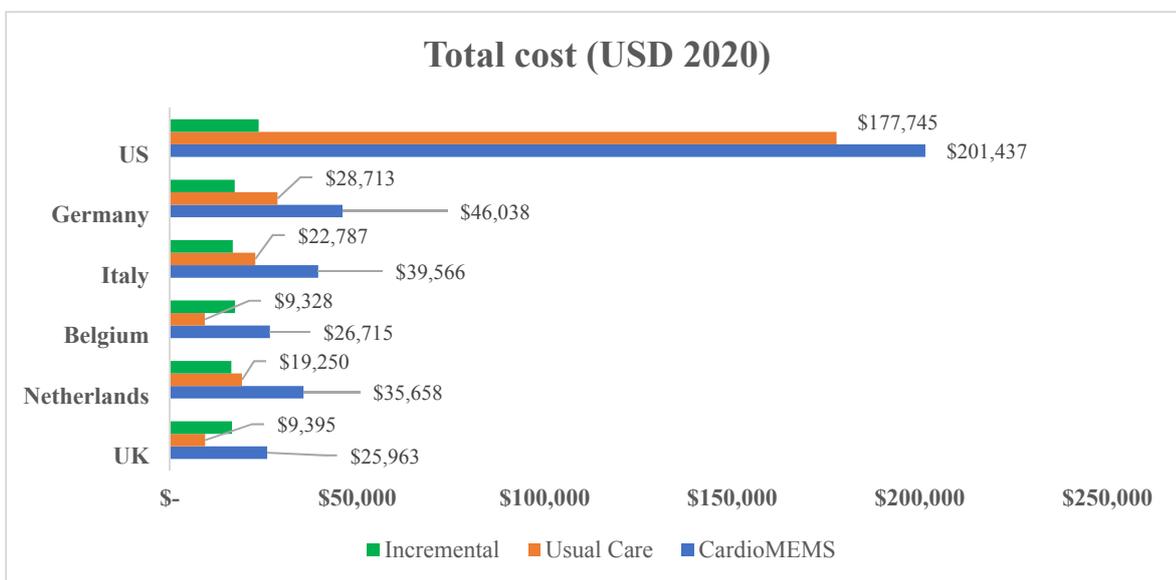


Figure 3. Total cost of CardioMEMS and usual care in different countries

higher QALYs for patients (2.73 vs 2.3). Possible reasons for higher QALYs in these patients include reduction of re-admission, reduction of mortality, and relative improvement of HF patients through continuous wireless monitoring. Figure 2 also shows that the CardioMEMS HF system has created higher LYQs for patients (4.71 vs 4.37), which is due to the reduction of mortality rate in this group of HF patients based on results from the CHAMPION trial (9, 11, 12).

Total Costs of CardioMEMS Versus SoC

Figure 3 shows the total cost for the CardioMEMS system and the SoC in different countries. Despite inherent differences in health care systems, in all selected countries, the CardioMEMS method is a more expensive method than the SoC for HF patients. The results of our study showed that the CardioMEMS method has the highest cost in the US

and Germany (US\$ 201,437 and US\$ 46,038) and the lowest cost in the UK and the Netherlands (US\$ 25,963 and US\$ 35,658), respectively. It is also observed that in countries such as the US, where the cardioMEMS system is expensive, the SoC is relatively expensive for caregivers and the health system, which indicates the high tariffs for health services in these countries (27). It is important to note that despite the high cost of services and interventions in a country like the US, this country has a much higher willingness to pay threshold compared with other countries such as the UK. For example, the cost-effectiveness threshold in the US is US\$100,000 to US\$150,000, while it is £20,000 (US\$ 27,600) to £30,000 (US\$ 41,400) in the UK, which makes a therapy or intervention more likely to be cost-effective in a country with a higher threshold.

Cost-effectiveness of CardioMEMS System in HF

The ICER is the most important indicator when deciding

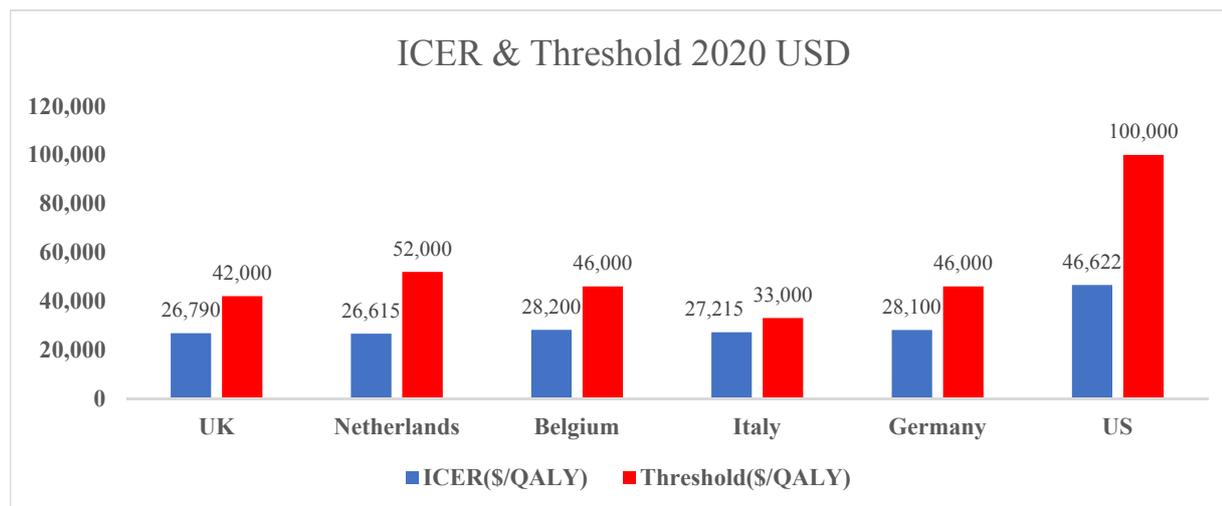


Figure 4. ICER and threshold in different countries.

about the cost-effectiveness of an intervention or health service. If the ICER value obtained is less than the acceptable threshold, the intervention is cost-effective in the defined health system (28, 29). In this study, the threshold for Germany, Italy, the Netherlands, and Belgium was considered equivalent to per capita income of 2019 in USD. Figure 4 shows the highest threshold (WTP) in the US and the lowest in Italy (US\$ 100,000 and US\$ 33,000 per QALY), respectively. Results of the present study showed that in all selected countries, the CardioMEMS is a cost-effective method for monitoring and managing pulmonary artery pressures in HF patients, as in all selected countries the obtained ICER value was lower than an acceptable threshold. Studies conducted in the US have reported different values for the ICER, these values vary from \$12,262/QALY to \$71,462/QALY. One of the reasons for this difference is the lower total 5-year cost in the study of Martinson et al (CardioMEMS, \$56,974 and control group, US\$ 52,149) compared with the study of Schimer et al (CardioMEMS, \$188,880 and SoC, \$162,772), while these 2 studies have provided almost the same values of QALYs for patients in the CardioMEMS group and the control group. Results showed that the most cost per QALY for the CardioMEMS system was in the US and the lowest was in the Netherlands (\$46,622 and \$26,615 per QALY), respectively. Also, the ICER index values obtained for all selected countries were in the range of \$27,000-28,000 per QALYs, except for the US, which indicates the proximity of costs in these countries.

Limitation

Despite its strengths of methodological rigor and the statistical robustness of the approaches utilized, some limitations affect the present investigation. First, in this systematic review, cost-effectiveness simulation studies formulated input assumptions based on the results from the CHAMPION trial, a trial included a minimum 6-month, single-blind period (with a mean of 18 months) and an additional mean 13-month open access period, long-term ef-

ficacy and safety data are not currently available and require assumptions about the sustainability of benefits over the long term. Second, a significant difference in costs of studies conducted in the US was observed, some of these differences are due to the different hospital and outpatient cost inputs utilized.

Conclusion

To conclude, evidence from this systematic review suggests that remote cardiac monitoring with the CardioMEMS system reduced hospitalization and mortality rate and improved both life expectancy and QALYs compared with the SoC in HF patients and it was also a cost-effective treatment option. Results showed that in all 6 selected countries (UK, Netherlands, Belgium, Italy, Germany, and US), the ICERs were well below the conventional threshold in different health care systems. Strategies such as CardioMEMS, which decrease the rate of hospitalization, are likely to be only more cost-effective in the future.

Abbreviations

HF, Heart failure
 LV, Left ventricle
 PAPs, Pulmonary artery pressures
 NYHA, New York Heart Association
 HFpEF, heart failure with preserved ejection fraction
 HFrEF, heart failure with reduced ejection fraction
 FDA, Food and Drug Administration
 ESC, European Society of Cardiology
 PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses
 NHS EED, National Health Service Economic Evaluation Database
 DARE, database of abstracts of reviews of effects
 HTA, health technology assessment
 ICER, Institute for Clinical and Economic Review
 NICE, National Institute for Health and Care Excellence
 QALYs, quality-adjusted life years
 LYG, life-years gained

ICER, incremental cost-effectiveness ratio
 CHEERS, the Consolidated Health Economic Evaluation Reporting Standards
 SoC, standard of Care
 WTP, willingness to pay

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Authors' Contributions

All authors contributed to the conceptual background and content of the publication.

Ethics Declarations

This study is an extract from the research project with the Code of Ethics IR.AJAUMS.REC.1399.238 from AJA University of Medical Sciences, Tehran, Iran.

Conflict of Interests

The authors declare that they have no competing interests.

References

1. Puggia I, Rowland TJ, Miyamoto SD, Sinagra G, Mestroni L. Chapter 1 - Molecular and Cellular Mechanisms in Heart Failure. In: Jefferies JL, Chang AC, Rossano JW, Shaddy RE, Towbin JA, editors. *Heart Failure in the Child and Young Adult*. Boston: Academic Press; 2018. p. 3-19.
2. Bragazzi NL, Zhong W, Shu J, Abu Much A, Lotan D, Grupper A, et al. Burden of heart failure and underlying causes in 195 countries and territories from 1990 to 2017. *Eur J Prev Cardiol*. 2021.
3. Ziaeian B, Fonarow G. Epidemiology and aetiology of heart failure. *Nat Rev Cardiol*. 2016;13(6):368-78.
4. Heidenreich PA, Albert NM, Allen LA, Bluemke DA, Butler J, Fonarow GC, et al. Forecasting the impact of heart failure in the United States: a policy statement from the American Heart Association. *Circ Heart Fail*. 2013;6(3):606-19.
5. Guha K, McDonagh T. Heart failure epidemiology: European perspective. *Curr Cardiol Rev*. 2013;9(2):123-7.
6. Martinson M, Bharmi R, Dalal N, Abraham WT, Adamson P. Pulmonary artery pressure-guided heart failure management: US cost-effectiveness analyses using the results of the CHAMPION clinical trial. *Eur J Heart Fail*. 2017;19(5):652-60.
7. Xue L, Yang Y, Sun B, Liu B, Zeng Q, Xiong C. Mildly Elevated Pulmonary Arterial Pressure Is Associated With a High Risk of Progression to Pulmonary Hypertension and Increased Mortality: A Systematic Review and Meta-Analysis. *J Am Heart Assoc*. 2021;10(7):e018374.
8. Hoepfer MM, Bogaard HJ, Condliffe R, Frantz R, Khanna D, Kurzyna M, et al. Definitions and diagnosis of pulmonary hypertension. *J Am Coll Cardiol*. 2013;62(25 Suppl):D42-50.
9. Abraham WT, Adamson PB, Hasan A, Bourge RC, Pamboukian SV, Aaron MF, et al. Safety and accuracy of a wireless pulmonary artery pressure monitoring system in patients with heart failure. *Am Heart J*. 2011;161(3):558-66.
10. Adamson PB, Magalski A, Braunschweig F, Böhm M, Reynolds D, Steinhilber D, et al. Ongoing right ventricular hemodynamics in heart failure: clinical value of measurements derived from an implantable monitoring system. *J Am Coll Cardiol*. 2003;41(4):565-71.
11. Abraham WT, Adamson PB, Bourge RC, Aaron MF, Costanzo MR, Stevenson LW, et al. Wireless pulmonary artery haemodynamic monitoring in chronic heart failure: a randomised controlled trial. *Lancet*. 2011;377(9766):658-66.
12. Adamson PB, Abraham WT, Aaron M, Aranda Jr JM, Bourge RC, Smith A, et al. CHAMPION trial rationale and design: the long-term safety and clinical efficacy of a wireless pulmonary artery pressure monitoring system. *J Card Fail*. 2011;17(1):3-10.
13. Kolominsky-Rabas PL, Kriza C, Djanatliev A, Meier F, Uffner S, Radeleff J, et al. Health economic impact of a pulmonary artery pressure

- sensor for heart failure telemonitoring: a dynamic simulation. *Telemed J E Health*. 2016;22(10):798-808.
14. Brugs J, Veenis JF, Radhoe S, Linssen G, van Gent M, Borleffs C, et al. A randomised comparison of the effect of haemodynamic monitoring with CardioMEMS in addition to standard care on quality of life and hospitalisations in patients with chronic heart failure. *Neth Heart J*. 2020;28(1):16-26.
15. Schmier JK, Fonarow G. Cost-Effectiveness of Remote Cardiac Monitoring With the CardioMEMS Heart Failure System. *Clin Cardiol*. 2017;40(7):430-6.
16. Ayyadurai P, Alkhwam H, Saad M, Al-Sadawi MA, Shah NN, Kosmas CE, et al. An update on the CardioMEMS pulmonary artery pressure sensor. *Ther Adv Cardiovasc Dis*. 2019;13:1753944719826826.
17. Cowie MR, Simon M, Klein L, Thokala P. The cost-effectiveness of real-time pulmonary artery pressure monitoring in heart failure patients: a European perspective. *Eur J Heart Fail*. 2017;19(5):661-9.
18. Wang SY, Valero-Elizondo J, Ali HJ, Pandey A, Cainzos-Achirica M, Krumholz HM, et al. Out-of-Pocket Annual Health Expenditures and Financial Toxicity From Healthcare Costs in Patients With Heart Failure in the United States. *J Am Heart Assoc*. 2021;10(14):e022164.
19. Moslehi S, Atefimanesh P, Asiabar AS, Ahmadzadeh N, Kafaeimehr M, Emamgholizadeh S. Does outsourcing paramedical departments of teaching hospitals affect educational status of the students? *Med J Islam Repub Iran*. 2016;30:404.
20. Jencks SF, Williams MV, Coleman EA. Rehospitalizations among patients in the Medicare fee-for-service program. *N Engl J Med*. 2009;360(14):1418-28.
21. Anderson JL, Heidenreich PA, Barnett PG, Creager MA, Fonarow GC, Gibbons RJ, et al. ACC/AHA statement on cost/value methodology in clinical practice guidelines and performance measures: a report of the American College of Cardiology/American Heart Association Task Force on Performance Measures and Task Force on Practice Guidelines. *J Am Coll Cardiol*. 2014;63(21):2304-22.
22. Manesh PA, Ardestani AS, Kermani B, Rezapour A, Asiabar AS. The relation characteristics of personality of managers working in Iran University of Medical Sciences with success and desirable job. *Med J Islam Repub Iran*. 2015;29:232.
23. Page MJ, Moher DJSr. Evaluations of the uptake and impact of the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) Statement and extensions: a scoping review. *Syst Rev*. 2017;6(1):263.
24. Sandhu AT, Goldhaber-Fiebert JD, Owens DK, Turakhia MP, Kaiser DW, Heidenreich PAJHF. Cost-effectiveness of implantable pulmonary artery pressure monitoring in chronic heart failure. *JACC Heart Fail*. 2016;4(5):368-75.
25. Ollendorf D, Sandhu A, Chapman R, Heidenreich P, Russo E, Shore K, et al. CardioMEMS™ HF System (St. Jude Medical) and sacubitril/valsartan (Entresto™, Novartis) for management of congestive heart failure: effectiveness, value, and value-based price benchmarks. *Institute for Clinical and Economic Review*. 2015 Sep 11.
26. Azari S, Rezapour A, Omidi N, Alipour V, Tajdini M, Sadeghian S, et al. A systematic review of the cost-effectiveness of heart valve replacement with a mechanical versus biological prosthesis in patients with heart valvular disease. *Heart Fail Rev*. 2020;25(3):495-503.
27. Luca L, Paul O. Price Setting and Price Regulation in Health Care Lessons for Advancing Universal Health Coverage: Lessons for Advancing Universal Health Coverage: OECD Publishing; 2019.
28. Brouwer W, van Baal P, van Exel J, Versteegh M. When is it too expensive? Cost-effectiveness thresholds and health care decision-making. *Springer; Eur J Health Econ*. 2019.
29. Cleemput I, Neyt M, Thiry N, De Laet C, Leys M. Using threshold values for cost per quality-adjusted life-year gained in healthcare decisions. *Int J Technol Assess Health Care*. 2011;27(1):71-6.