Pulmonary artery pressure-guided heart failure management: US cost-effectiveness analyses using the results of the CHAMPION clinical trial

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Aims	Haemodynamic-guided heart failure (HF) management effectively reduces decompensation events and need for hospitalizations. The economic benefit of clinical improvement requires further study.
Methods and results	An estimate of the cost-effectiveness of haemodynamic-guided HF management was made based on observations published in the randomized, prospective single-blinded CHAMPION trial. A comprehensive analysis was performed including healthcare utilization event rates, survival, and quality of life demonstrated in the randomized portion of the trial (18 months). Markov modelling with Monte Carlo simulation was used to approximate comprehensive costs and quality-adjusted life years (QALYs) from a payer perspective. Unit costs were estimated using the Truven Health MarketScan database from April 2008 to March 2013. Over a 5-year horizon, patients in the Treatment group had average QALYs of 2.56 with a total cost of US$56 974; patients in the Control group had QALYs of 2.16 with a total cost of US$52 149. The incremental cost-effectiveness ratio (ICER) was US$12 262 per QALY.Using comprehensive cost modelling, including all anticipated costs of HF and non-HF hospitalizations, physician visits, prescription drugs, long-term care, and outpatient hospital visits over 5 years, the Treatment group had a total cost of US$212 004 and the Control group had a total cost of US$200 360. The ICER was US$29 593 per QALY.
Conclusions	Standard economic modelling suggests that pulmonary artery pressure-guided management of HF using the CardioMEMS™ HF System is cost-effective from the US-payer perspective. This analysis provides the background for further modelling in specific country healthcare systems and cost structures.
Keywords	Economic analysis ● Congestive heart failure ● Haemodynamic monitoring ● Heart failure hospitalization

Introduction

Heart failure (HF) is a complex clinical syndrome and global public health problem affecting an estimated 26 million people worldwide.[1] Despite increased utilization of pharmacological[2–9] and device therapy options[10–13] that improve clinical outcomes in randomized controlled trials, morbidity and mortality in HF remain a major burden to patients, their caregivers, and national healthcare systems. Patients with HF frequently experience worsening symptoms related to accumulation of excess intravascular volume and congestion, requiring hospitalization to provide intravenous medical support to restore normal volume.[14–19] Heart failure is cited as the most frequent cause of hospitalization in the US Medicare population, resulting in >1 million admissions per year (accounting for 1–2% of all hospitalizations).[20,21] The economic impact of HF in the USA is profound, with the total costs of HF estimated to

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increase from US$31 billion in 2012 to US$70 billion in 2030 secondary to an ageing population.[22] Cost-effective HF management strategies are required to address this growing problem.

Elevated cardiac filling pressures are associated with higher rates of re-hospitalization and mortality in patients with HF.[23,24] Independent of LVEF, rises in cardiac filling pressures can often be detected several weeks prior to patients experiencing symptoms of HF decompensation that require hospitalization.[25,26] Remote monitoring of intracardiac and pulmonary artery pressures (PAPs) in patients with HF using implantable haemodynamic 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.[27−30] A novel wireless PAP measurement system (CardioMEMS™ HF System, St. Jude Medical, Inc., Atlanta, GA, USA) was evaluated in the CardioMEMS™ Heart Sensor Allows Monitoring of Pressure to Improve Outcomes in New York Heart Association (NYHA) functional Class III Heart Failure Patients (CHAMPION) trial.[30,31] The CHAMPION trial was a prospective, multicentre, randomized, single-blind clinical study in 550 patients that tested the incremental impact of PAP-guided HF management on clinical outcomes compared with HF management based on current American College of Cardiology Foundation/American Heart Association practice guidelines only.

The PAP-guided HF management group in the CHAMPION trial experienced a significant reduction in HF hospitalization rates, a greater reduction in PAPs, fewer patients hospitalized for HF, and more days alive and outside of the hospital for HF, and exhibited an improvement in quality of life when compared with guideline-directed standard of care HF management only (Control group).[30] These long-term benefits were seen in patients with HF and preserved EF,[32] secondary pulmonary hypertension,[33] and co-morbid chronic obstructive CAD.[34] Hospitalization reductions were seen after an average of 18 months of randomized follow-up, with additional long-term benefits noted in the 13 months of 'open-access', which immediately followed the end of the randomized follow-up in the trial.[35] Based on these data, the CardioMEMS™ HF System was approved by the US Food and Drug Administration for HF management in NYHA class III HF patients with a HF hospitalization within the last 12 months. This study is a comprehensive analysis of the cost-effectiveness of this treatment strategy in the context of the US medical system.

Methods

A Markov model was utilized to approximate the course of management observed in the CHAMPION trial for the Treatment and Control groups using Monte Carlo simulation. The objective was to estimate the costs and cost-effectiveness over a time horizon extended beyond the study follow-up period. Healthcare utilization event rates, survival, and quality of life were based on study data. We took the perspective of the payer, and focused on the Medicare and private insurance patient populations as they represent the vast majority of patients eligible for the CardioMEMS™ HF System in the USA, and cost data were available for these two patient populations to conduct our analyses. Model endpoints included cost of treatment and preference-weighted
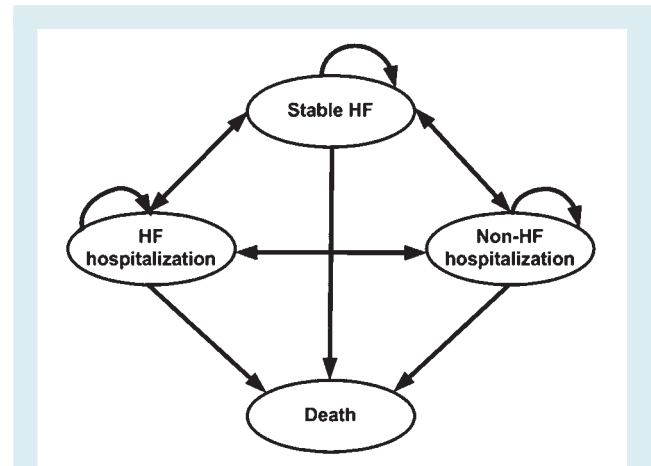

Figure 1 Markov model used to approximate the course of management observed in the CHAMPION trial for the Treatment and Control groups. HF, heart failure.

survival, which were then used to calculate incremental cost per life year gained and cost per quality-adjusted life year (QALY) gained for the treatment compared with control.

Model structure

The Markov model employed four states: 'stable HF', 'hospitalized for HF', 'hospitalized for other cause', and 'death' (*Figure 1*). Each simulated patient transitioned through the states in cycles of 1 month, incurring costs and accumulating effects associated with each state. The total time horizon of the simulation for the base case was 5 years (or 60 cycles). Costs and effects were discounted at 3% per year.[36] A total of 100 000 patients were simulated in each group.

A patient in the 'stable HF' state was characterized as a patient that received typical care for HF including physician visits, prescription drugs, long-term care, and outpatient hospital visits. A patient in the 'hospitalized for HF' state was characterized as a patient undergoing inpatient hospitalization related to a primary diagnosis of HF. Since the average length of stay for a HF hospitalization in the USA is 5.2 days for all patients according to the Healthcare cost and utilization project (HCUP) National statistics (2012),[37] we assumed that in this state, a patient incurred the same expense as in the 'stable HF' state in addition to the cost of HF hospitalization. In the model simulation, patients in the Control group started in the 'stable HF' state, and the Treatment group started the simulation with an implant-related hospitalization.

A patient in the 'hospitalized for other cause' state was characterized as a patient undergoing inpatient hospitalization for any reason other than a primary diagnosis of HF. Since the average length of stay for a hospitalization for any cause in the USA is 4.5 days for all patients according to the HCUP National statistics (2012),[37] we assumed that in this state, a patient incurred the same expense as in the 'stable HF' state in addition to the cost of other-cause hospitalization. 'Death' was an absorbing state.

As part of the prospective CHAMPION trial design, all patients initially underwent implantation of the PAP sensor prior to randomization. All patients then remained in their randomized study group until the last patient to be enrolled completed at least 6 months of study follow-up (Randomized Access Period). At the conclusion of the Randomized Access Period, all active patients transitioned to a follow-up

period where study physicians then had access to PAP information for all patients (Open Access Period). For this cost-effectiveness analysis (CEA), estimates of the transition probabilities among states, mortality, and EQ-5D preference weight utilities in each state came from the complete Randomized Access Period of the CHAMPION trial (*Table 1*). All hospitalizations were adjudicated by a Clinical Event Classification (CEC) committee as part of the CHAMPION trial and classified in one of two ways: inpatient hospitalization associated with HF or inpatient hospitalization not associated with HF.

Health-related quality of life (HRQoL) was assessed via the EQ-5D-3 L[38] questionnaire at baseline, 6 months, and 12 months in the CHAMPION trial. For the model, HRQoL at 12 months was carried forward for the 60-month model. We utilized US population-based EQ-5D-3 L preference weights for this economic analysis.[39] QALYs were accumulated based on the assumption that the preference weight was constant between measurement intervals.

Cost of healthcare utilization

Currently, the USA has no single national system of health insurance. Health insurance is purchased in the private marketplace or provided by the government to certain groups (e.g. Medicare insurance to the elderly and disabled population). Because of this, we used a payer mix based on the age distribution in the CHAMPION study cohort. Patients less than 65 years old at implant were assumed to be paid through private insurance, and those 65 years or older at implant were assumed to be paid by Medicare.

In the USA, the implant of the CardioMEMS™ HF System is associated with the MS-DRG (Medicare Severity Diagnosis Related Groups) payment for 264 accompanied by the ICD-9-CM (International Classification of Diseases, Ninth Revision, Clinical Modification) procedure code of 38.26: insertion of an implantable pressure sensor without a lead for intracardiac or great vessel haemodynamic monitoring. In the base case, the cost of system implantation in the Treatment group was US$17 750[40] and we made the assumption that all implants occurred on a unique scheduled day for each patient, and did not occur during a pre-existing HF hospitalization.

Payer costs for hospitalizations post-implant (which are reimbursements) were determined from the Truven Health MarketScan® April 2008 to March 2013 Commercial Claims and Encounters and Medicare Supplemental and Coordination of Benefits Database. This MarketScan® database represents the de-identified health services of employees, dependents, and retirees in the USA with primary or Medicare supplemental coverage through privately insured fee-for-service, point-of-service, or capitated health plans. Overall, it includes ~20% of the US population across all 50 states. All enrolment records and inpatient, outpatient, ancillary, and drug claims were tabulated.

We identified a HF cohort from this claims database by ascertaining patients with an inpatient hospitalization with primary diagnosis of HF (ICD-9-CM diagnosis code of 428.X). The HF cohort consisted of 200 471 patients that had Medicare advantage insurance and private insurance. The Medicare patients consisted of 50% male patients with an average age of 80 ± 8 years. The private insurance patients consisted of 60% male patients with an average age of 57 ± 9 years. The distribution of geographic locations for all patients were: Northeast (20%), North Central (33%), South (31%), and West (14%). In this HF cohort, we identified payments for three types of healthcare utilization: average cost of inpatient hospitalization with primary diagnosis code of HF, average cost of inpatient hospitalization not related to HF, and annual costs for outpatient healthcare utilization of any type for

these patients (*Table 2*). These payments corresponded to the states of 'hospitalized for HF', 'hospitalized for other cause', and 'stable HF' in the model. The payments included facility cost and professional fees associated with the event, adjusted to 2014 US dollars based on the consumer price index (CPI) inflation from the Bureau of Labor Statistics.

The costs related to 'stable HF' included the majority of expenses a non-hospitalized HF patient incurs receiving medical care; this included physician visits, prescription drugs, long-term care, and outpatient hospital visits. In addition to this, a patient implanted with the CardioMEMS™ HF System was assumed to incur a monthly cost of US$45 associated with the professional and technical components of reimbursement for remote physiological monitoring. Since remote physiological monitoring is conducted for various reasons for patients that have not been implanted with the CardioMEMS™ HF System, we assumed that 25% of the standard of care patients also incur this monthly cost.

The CHAMPION trial reported eight device- and system-related complications (DSRCs) during 575 implant attempts.[3] All of these events occurred within the first 30 days of implant. Using the details from hospital admission and discharge records for each one of the eight DSRCs, we ascertained an MS-DRG for each such hospitalization, and then determined an average cost of DSRCs based on the 2014 reimbursement for the MS-DRGs. No further device- or system-related complications or sensor failures were reported in an average of 31 months following implant.[36]

Cost-effectiveness outcome measures

The primary efficacy endpoint of the CHAMPION trial was the rate of HF-related hospitalizations. Thus, our primary effectiveness endpoint was the incremental cost-effectiveness ratio (ICER) comparing the costs and QALYs of HF hospitalization outcomes in the PAP Treatment and Control groups. The model was used to extrapolate this endpoint to 5 years.

One-way sensitivity analyses were performed to assess the impact of varying selected model parameters while holding other variables fixed at their base case values. These parameters included HF hospitalization rates, mortality rates, cost of HF hospitalization, monitor implant cost, and payer mix. The goal was to understand how robust the base case results were to uncertainty about the values used. In addition, sensitivity analyses were conducted on the costs included in the analysis: HF hospitalizations only, all-cause hospitalizations, and all chronic HF management costs including all-cause hospitalizations. Two probabilistic sensitivity analyses (PSAs) were performed with 100 000 resamples of the model parameters to examine the impact of their combined uncertainty. Tabulation of distributions used for the parameters in the probabilistic sensitivity analyses are provided in the Supplementary material online, *Table S1*. An assumption in this model is that the outpatient costs increase due to an improved survival benefit (not due to other changes).

Results

Primary cost-effectiveness analysis: comparison of heart failure hospitalization outcomes

The purpose of PAP monitoring via CardioMEMS was to reduce HF hospitalizations, hence the primary CEA focused on comparing HF

Table 1 Long-term clinical outcomes from CHAMPION trial Randomized Access Period[35]

	Treatment group (n = 270)	Control group (n = 280)	
Heart failure hospitalizations, n (events/patient-year)	182 (0.46)	279 (0.68)	Diff 97 (0.23), NNT 4, HR 0.67 (33% RRR) (95% CI 0.55−0.80), P < 0.0001[a]
Non heart failure hospitalizations, n (events/patient-year)	372 (0.93)	393 (0.96)	Diff 21 (0.03), HR 0.97 (3% RRR) (95% CI 0.84−1.12), P = 0.6790[a]
Death, n (%)	50 (18.5%)	64 (22.9%)	Non-significant, HR 0.80 (95% CI 0.55−1.15), P = 0.23[b]
EQ-5D-3 L utilities (US preference weights)			
Baseline	0.711		
6 months	0.719	0.681	P = 0.056[c]
12 months	0.739	0.660	P = 0.003[c]

NNT, number needed to treat; RRR, relative risk reduction.
[a]Hazard ratio (HR), 95% confidence interval (CI), and P-value from the Andersen−Gill model.
[b]HR and 95% CI from the Cox proportional hazards model, P-value from log-rank test.
[c]P-value from two-sided Wilcoxon test.

Table 2 Post-implant healthcare utilization from MarketScan®

	Medicare	Private insurance
Treatment reimbursement from cohort of 200 471 HF patients (MarketScan®)		
Average reimbursement per HF hospitalization (US$/event)	US$16 770	US$30 100
Average reimbursement per non-HF hospitalization (US$/event)	US$20 290	US$32 400
Annual outpatient healthcare utilization (US$/year)	US$17 288	US$23 067

HF, heart failure.

hospitalization outcomes. The costs associated with HF hospitalizations, device- and system-related complications, and remote physiological monitoring were accumulated. Over a 5-year time horizon, patients in the Treatment group had average QALYs of 2.56 (discounted at 3%) with a total cost of US$56 974; patients in the Control group had QALYs of 2.16 with a total cost of US$52 149. The ICER was US$12 262 per QALY (Table 3).

Sensitivity analyses of cost sources

Cost-effectiveness analysis: comparing all-cause hospitalization outcomes

Heart failure management is expensive, and, historically, studies related to CRT management of HF patients have compared all-cause hospitalization outcomes. Although the CardioMEMS™ HF System did not have a significant impact on non-HF-related hospitalizations, we compared all hospitalizations for the two groups to enable a comparison with historical studies. The costs associated with all-cause hospitalizations, device- and system-related complications, and remote physiological monitoring were accumulated. Over a 5-year time horizon, patients in the Treatment group had average QALYs of 2.56 (discounted at 3%) with a total cost of US$140 966; patients in the Control group had QALYs of 2.16 with a total cost of US$133 681. The ICER was US18 515 per QALY (Table 3).

Cost-effectiveness analysis: comparing comprehensive management

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. To these were added the costs of patient management, which include HF and non-HF hospitalizations, physician visits, prescription drugs, long-term care, and outpatient hospital visits. Over the 5-year time period, patients in the Treatment group had a total cost of US$212 004 and patients in the Control group had a total cost of US$200 360. The ICER was US$29 593 per QALY (Table 3).

One-way sensitivity analyses

The ICER was sensitive to the time horizon (Figure 2). Compared with the base case ICER of US$12 262/QALY at 5 years, the ICERs at 4 years and 7 years were US$34 909/QALY and US$5412/QALY, respectively. The ICERs decreased over time; this is a common observation when a high-cost procedure occurs at the beginning of the time horizon, indicating that the therapy is cost-effective primarily resulting from averted hospitalizations.

Table 3 Cost-effectiveness analysis base-case costs and survival over a 5-year time horizon

	Primary CEA endpoint: HF hospitalization outcomes		All-cause hospitalization outcomes		Comprehensive patient management outcomes	
	Treatment group	Control group	Treatment group	Control group	Treatment group	Control group
Cumulative average cost	US$56 974	US$ 52 149	US$140 966	US$133 681	US$212 004	US$200 360
Cumulative QALYs	2.56	2.16	2.56	2.16	2.56	2.16
Cumulative average years survival	3.70	3.47	3.70	3.47	3.70	3.47
Incremental cost effectiveness ratio (US$/QALY)	US$12 262		US$18 515		US$29592	
Cost reduction for each patient under treatment post implant (US$/year)[a]	US$4443		US$5261		US$5296	

CEA, cost-effectiveness analysis; HF, heart failure; QALY, quality adjusted life year.
[a]Cost saving per life year for the treatment group.
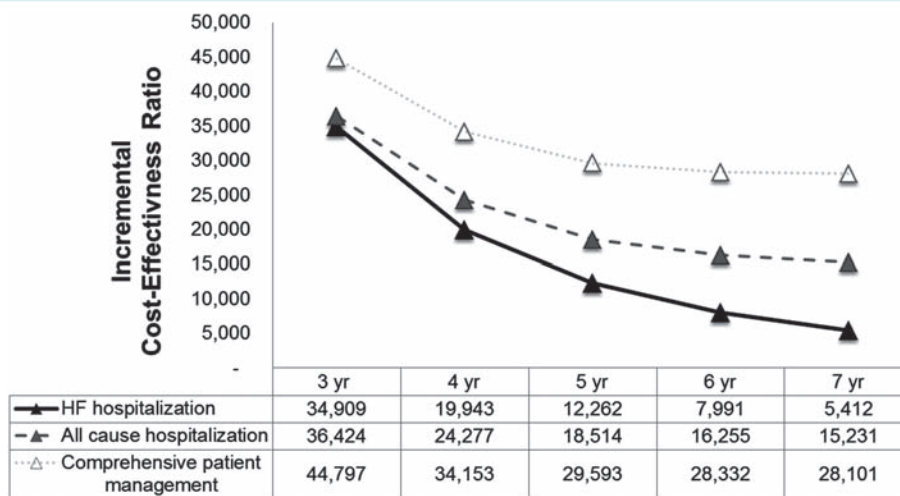
Figure 2 Time horizon analysis: incremental cost-effectiveness ratios vs. time horizon (3–7 years). HF, heart failure; yr, year.

The ICERs were also assessed when HF hospitalization rates, HF hospitalization costs, and mortality rates were varied. These are reported in the tornado plot on *Figure 3*. The ICERs varied between US$10 960/QALY and US$14 311/QALY when HF hospitalization rate varied between the 95% confidence interval of the hospitalization rates from the CHAMPION trial. The sensitivity around HF hospitalization cost showed the ICERs to vary between −US$6172/QALY and US$30 696/QALY. When the cost of HF hospitalization was 50% higher than the base case, the ICER at a 5-year time horizon of −US$6172 resulted from the treatment arm accumulating lower costs compared with the control arm. The ICERs varied between US$8456/QALY and US$16 854/QALY when the mortality rates varied between the 95% confidence bounds of the CHAMPION trial mortality rates.

The ICER was sensitive to the implant cost, and for an implant cost range of US$15 556 to US$26 704, the ICER ranged from US$6686/QALY and US$35 018/QALY. The implant costs—low and high ranges—were determined using the national DRG payment for MS-DRG code 264 with and without the new technology add-on payment (NTAP) in the case of the inpatient hospitalizations, and the APC (Ambulatory Payment Classification) code 0319 with and without the Pass-Through payment.

According to the HCUP NIS (Nationwide inpatient sample) data set from 2012,[37] amongst all inpatient hospitalizations associated with a primary or secondary diagnosis of HF identified via ICD-9-CM code 428.X, there were 5 021 800 discharges for HF with the payer as Medicare, and 674 680 discharges for HF in patients that had private insurance. Using these two payer
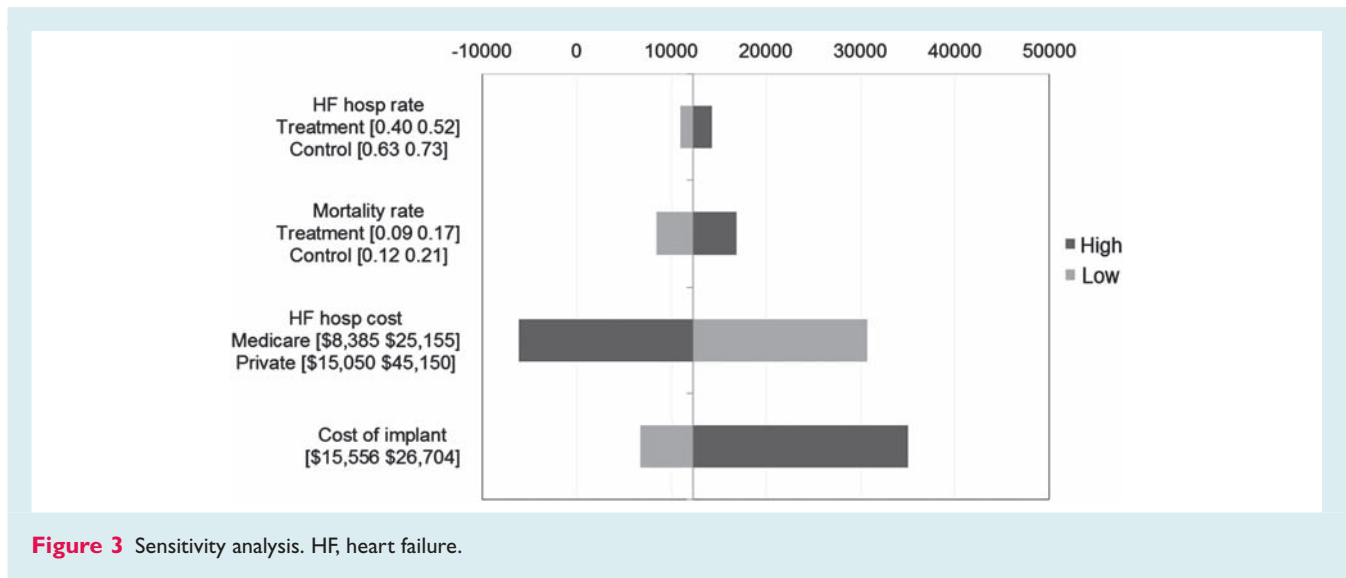
Figure 3 Sensitivity analysis. HF, heart failure.

categories (Medicare and private payer), 88% of HF hospitalizations occurred in Medicare beneficiaries. Using this 88% (Medicare) and 12% (private insurance) distribution to form the assumption of patient mix, the ICER was US$20 734/QALY.

Probabilistic sensitivity analyses

For the primary CEA (using HF hospitalization costs only), the PSA showed that at the willingness-to-pay threshold of US$25 000, >85% of the simulations were cost-effective; >99% were cost-effective at the US$50 000 threshold. Further, for the CEA using comprehensive patient management costs, the PSA showed that at the willingness-to-pay threshold of US$50 000, 87% of the simulations were cost-effective; >99% were so at the US$100 000 threshold. The cost-effectiveness acceptability is shown in the Supplementary material online, *Figures S1–S4*.

Discussion

This study demonstrated that haemodynamic-guided HF management is a cost-effective strategy to improve outcomes in outpatient management of patients with chronic HF. Cost-effectiveness calculations determined that this strategy was well below the most commonly used threshold of US$50 000 per QALY. This threshold has become an accepted benchmark for cost-effectiveness in the USA and is often attributed to the US decision to mandate Medicare coverage for patients with end-stage renal disease in the 1970s.[41] Some economists as well as the World Health Organization (WHO) have argued, on the basis of plausible assumptions about people's values and attitudes toward risk, for a threshold of 2–3 times the per capita annual income, which would imply a US threshold of US$110 000 to US$160 000 per QALY.[42] This, indeed, would be a contemporary estimate of the costs of treating end-stage renal disease with haemodialysis.

Various factors result in a therapy being cost-effective, and in the case of PAP-guided HF care, the cost-effectiveness is attributable to the reduction in HF hospitalization rates, reduction in mortality, and improvement in quality of life. For the base case, as well as all-cost sensitivity analyses, the ICERs were shown to be consistently below the US$50 000/QALY maximum acceptable threshold. An important determinant of cost-effectiveness is the reimbursement for the system implantation. CardioMEMS™ is a new technology and in early stages of the reimbursement cycle. The uncertainty around the implant reimbursement was handled in our model by a sensitivity analysis around the implant cost range of US$15 556 and US$26 704. For this wide range, the therapy was shown to be consistently cost-effective.

Management of HF with pharmacological therapies and implantable device therapy has been studied extensively to prove their clinical effectiveness.[43] The ICERs for medical device therapy for HF patients are between US$10 900 and US$303 000/QALY, depending on the intervention considered. Cost-effectiveness of pharmacological therapies such as ACE inhibitors, ARBs, and beta-blockers has been assessed in the USA and Europe, and they have been shown to be cost-effective, with ICERs over a lifetime lower than US$17 900/QALY. Implantable cardioverter defibrillators (ICDs), CRT-P pacemakers, and CRT-D defibrillations have been evaluated in the HF population for which these devices are known to have clinical benefit. Cost-effectiveness studies of ICDs are sensitive to the patient population selected in each individual trial, and ICERs vary from US$34 000 to > US$70 000 per QALY gained over a lifetime.[43] ICERs across countries are variable due to variations in healthcare practices and prices. As an illustration, Feldman *et al.* showed that the ICER for CRT-P vs. optimal medical therapy is US$22 900/QALY in the USA; an ICER of US$10 900–US$29 700 in the UK; an ICER of US$37 200/QALY in Spain, and an ICER of US$14 600/QALY in Belgium.[44]

The COMPANION trial, for example, conducted a comparison of CRT-P vs. optimal medical therapy and CRT-D vs. optimal medical therapy. Implant costs for a CRT-D were assumed to be US$29 500 and for a CRT-P were US$20 500. Inclusion criteria included NYHA functional class III or IV plus a HF treatment in the

preceding 12 months over and above other criteria. The ICERs for CRT-P and CRT-D vs. optimal medical therapy were US$19 600 and US$43 000, respectively, over a 7-year time horizon.[44] Using the CPI for medical care inflation of an average of 4.03%, the ICER for CRT-P vs. optimal medical therapy and CRT-D vs. optimal medical therapy would be US$27 513/QALY and US$60 360/QALY, respectively. Modelling the CHAMPION trial cost-effectiveness over a 7-year time horizon and using all-cause hospitalization costs, which is similar to the methods used in COMPANION, compares favourably with this at US$15 231/QALY (US$ 2014).

An independent CEA was developed by Sandhu *et al.*[45] that concluded that the CardioMEMS device is cost-effective with an ICER of US$82 301 in patients with reduced EF and US$47 768 in those with preserved EF. Our analysis produced different estimates of the ICERs for several reasons: first, Sandhu *et al.* used a societal perspective and modelled lifetime costs and effects. Our model used a payer perspective and modelled costs and effects over 5 years. Secondly, the parameter estimates in the Sandhu model differed from those in our model. For example, Sandhu and colleagues assumed the cost of a HF hospitalization in the USA to be US$12 832. Our analysis used real-world claims data from 200 471 HF patients, which demonstrated an average payer cost of US$16 770 for Medicare and US$30 100 for private insurance patients. Thirdly, Sandhu and colleagues mapped MLHFQ (Minnesota Living with Heart Failure Questionnaire) scores into the EQ-5D scores based on an existing algorithm, which is an acceptable method, but inferior to direct measurement of utilities. Our analysis used the EQ-5D utilities which were measured at baseline and several times during follow-up in the CHAMPION trial. Finally, Sandhu *et al.* used mortality rates based on the relative risk of death associated with hospitalization; our analysis used mortality rates observed in the CHAMPION trial. Methodological differences in the model perspective, time horizon, and parameters resulted in different estimates of the ICER. However, both our analysis and the report from Sandhu *et al.* conclude that using the CardioMEMS HF System to manage HF patients is cost-effective in the US setting.

In spite of introduction of effective HF medical and device therapies, HF hospitalizations continue to rise and population-based HF mortality remains high. Over half the significant US cost of HF management arises due to hospitalization. Average annual medical expenditures per Medicare HF beneficiary are estimated to be US$33 247,[46] with total annual Medicare costs estimated at US$40 billion. Reductions in hospitalizations seen in the CHAMPION trial are very encouraging and suggest that haemodynamic monitoring of HF patients will provide a much-needed tool to assist outpatient management of high-risk patients. Hospitalizations due to all causes were also reduced in the CHAMPION Treatment group. Detailed information about guideline-directed medical therapy use at baseline and changes during the 6 months of haemodynamic-guided care in the CHAMPION trial was recently published by Costanzo *et al.*[47] Both the control and treatment groups started the trial with high prevalence of guideline-directed medical therapies at baseline at target doses. Both groups were receiving significantly higher doses of loop diuretics at the end of the 6-month efficacy endpoint; however, more increases and decreases in diuretics were seen in the

treatment group compared with the controls. Additionally, treatment group patients had significant increases in neurohormonal intervention and vasodilator therapies, which were not seen in the control group. The trial demonstrated that active personalization of HF management, guided by frequent haemodynamic assessment, was associated with less need for hospitalization and improvement in delivery of disease-modifying medications.

Within the US healthcare system, management of HF using a PAP sensor is expected to impact further readmissions within 30 days of discharge. The Centers for Medicare and Medicaid Services (CMS) has instituted financial penalties for hospitals with a higher than expected HF readmission rate for Medicare patients. The potential impact of the CardioMEMS HF System on HF 30-day readmissions was not studied in this model. Adoption of this treatment strategy at hospitals struggling with HF hospitalization and 30-day readmissions could potentially help address an unmet need within the US healthcare system, and may be addressed in separate analyses.

Heart failure is a global burden; while it is reasonable to expect that the clinical outcomes in Europe would be similar to those found in the current US-based study, a direct cost comparison using simple currency translation is not an accurate method to assess the economic impact in Europe. Hence, we present here a CEA study from the US payer perspective and expect that this will pave the way for future studies in individual countries wherein the unique measures that are relevant to each healthcare system and cost structure for each country are appropriately dealt with. The largest costs in our primary CEA are the implant hospitalization cost and the HF hospitalization cost. This study includes a sensitivity analysis using the cost of HF hospitalization at US$8358–US$25 155. The costs for HF hospitalizations in many European countries are quite variable and sometimes much lower; for example at £2515 in the UK and €2400 in Germany. For the lower of the two, assuming the same cost of implant as the US model, the ICER would be US$45 002/QALY.

Conclusions

The model suggests that PAP-guided management of HF is cost-effective. The ICERs, when considered for HF management or comprehensive management, were well below the conventional US acceptability threshold of US$50 000.

Heart failure remains an increasing global problem.[22,48] Coupled with the ageing population and thus increasing numbers of HF patients, the pressure on healthcare payers to reduce hospitalizations will continue unabated. Strategies such as CardioMEMS, which decrease the rate of hospitalization, are likely to be only more cost-effective in future.

Supplementary Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Distributions used for parameters in the probabilistic sensitivity analysis.

Conflict of interest: M.MM. and W.T.A. are Consultants to St. Jude Medical; R.B., N.D., and P.B.A. are employees of St. Jude Medical.

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