Cost-effectiveness of a Digital Health Intervention for Acute Myocardial Infarction Recovery

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Background: Acute myocardial infarction (AMI) is a common cause of hospital admissions, readmissions, and mortality worldwide. Digital health interventions (DHIs) that promote self-management, adherence to guideline-directed therapy, and cardiovascular risk reduction may improve health outcomes in this population. The “Corrie” DHI consists of a smartphone application, smartwatch, and wireless blood pressure monitor to support medication tracking, education, vital signs monitoring, and care coordination. We aimed to assess the cost-effectiveness of this DHI plus standard of care in reducing 30-day readmissions among AMI patients in comparison to standard of care alone.

Methods: A Markov model was used to explore cost-effectiveness from the hospital perspective. The time horizon of the analysis was 1 year, with 30-day cycles, using inflation-adjusted cost data with no discount rate. Currencies were quantified in US dollars, and effectiveness was measured in quality-adjusted life-years (QALYs). The results were interpreted as an incremental cost-effectiveness ratio at a threshold of $100,000 per QALY. Univariate sensitivity and multivariate probabilistic sensitivity analyses tested model uncertainty.

Results: The DHI reduced costs and increased QALYs on average, dominating standard of care in 99.7% of simulations in the

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Reducing hospital readmissions has become a major health policy goal in the United States to reduce potentially avoidable costs. A recent Medicare report showed that up to 76% of 30-day readmissions are potentially preventable by adhering to postdischarge care practices. Acute myocardial infarction (AMI) is a significant driver of readmissions and is a priority condition for the Hospital Readmissions Reductions Program (HRRP). Among >1 million patients in the United States hospitalized with AMI, nearly 1 in 6 experience an all-cause, unplanned, non-reimbursable readmission within 30 days postdischarge, costing the health care system over 1 billion dollars annually. In addition, Medicare penalties targeting 3241 eligible hospitals reached $564 million in 2018, up from $528 million in 2017.

Digital health interventions (DHIs) have the potential to reduce cardiovascular disease (CVD) risk factors and improve outcomes. The Corrie Health Digital Platform (Corrie) is a smartphone-based application developed in collaboration between patients, researchers, designers, engineers, and clinicians at Johns Hopkins University and Apple (Cupertino, CA). The DHI aims to empower patients in their own postdischarge recovery, improve the patient experience, and reduce hospital readmissions and keep patients connected to clinicians. Due to the scalability of DHIs and the ability to improve patient outcomes, there is significant potential for cost-savings for the health care system. Cost-effectiveness analyses have been used to study DHIs in the areas of telemedicine, cardiac rehabilitation, and weight management; however, studies evaluating smartphone-based interventions in AMI are scarce.

Therefore, the current analysis aims to conduct an economic evaluation, from the hospital perspective, of the cost-effectiveness of the Corrie DHI plus standard of care in reducing 30-day readmissions when compared with standard of care alone in AMI care. The evaluation specifically aims to identify the cost savings to the hospital from the introduction of the DHI. The evaluation would not, therefore, include an analysis of the cost savings from a societal perspective. We hypothesize that the Corrie DHI plus standard of care is cost-effective compared with standard of care alone at a willingness-to-pay threshold of $100,000 per quality-adjusted life-year (QALY).

METHODS

The Myocardial infarction, COMbined-device, Recovery Enhancement Study

The Johns Hopkins Myocardial infarction, COMbined-device, Recovery Enhancement (MiCORE) study was approved by the Johns Hopkins School of Medicine Institutional Review Board (IRB00099938) and was registered on clinicaltrials.gov (NCT03760796). Further information about the MiCORE study’s objectives and methodology has been described in detail in the rationale and design paper. In brief, this study’s primary objective was to determine if AMI patients using the DHI had lower rates of first all-cause unplanned 30-day readmissions as compared with a historical standard of the care control group. Patients admitted to Johns Hopkins Hospital, Johns Hopkins Bayview Medical Center, Massachusetts General Hospital, and Reading Hospital for an ST-elevation myocardial infarction (MI) or type 1 non-ST-elevation MI from October 1, 2016, to April 14, 2019, were enrolled prospectively into the DHI group if they: (1) were 18 years or older; (2) were English speaking; (3) owned a smartphone; (4) had no visual, auditory, cognitive, or motor impairment that would preclude DHI use; (5) were hemodynamically stable; and (6) were approved to participate by his/her inpatient care team. The historical control group consisted of English-speaking patients, 18 years or older, admitted to 1 of the 4 hospitals with an ST-elevation MI or non-ST-elevation MI from September 27, 2015, to October 1, 2016, before the availability of the DHI. Patients were excluded from the historical control group if they were ineligible for readmission, meaning that they experienced an in-hospital death or were transferred to another hospital at the time of discharge. If patients were transferred to another hospital at the time of discharge, then the hospital at which they were enrolled would no longer be the hospital subject to penalties in the case of 30-day readmission. Ultimately, 200 participants were enrolled in the DHI group and 864 in the historical control group.

After enrollment into the DHI group, study researchers assisted the participant with downloading the Corrie app onto the participant’s personal iPhone, or the participant was given an “iShare,” which was a refurbished iPhone preloaded with Corrie and equipped with a subscriber identity module card. Participants were given an iShare if they owned an Android, or iPhone 5 or older iPhone model as these smartphones were not compatible with the Corrie app. The Health Insurance Portability and Accountability Act (HIPAA)-compliant DHI consists of: (1) a smartphone application; (2) cooperative sensors including an Apple Watch and an iHealth wireless blood pressure monitor (model BPL3); and (3) a data backend.

The DHI integrates constructs from the widely accepted Health Belief Model and Social Cognitive Theory to promote health behavior change. The DHI allowed participants to: (1) manage their medications (track daily adherence, indication, and side effects); (2) monitor their vital signs (heart rate, blood pressure, weight, mood, and steps); (3) learn about the risk factors for CVD, and lifestyle modification through educational articles (all at a sixth-grade or seventh-grade reading level as determined by the Flesch-Kincaid Readability Test Tool) and animated videos (Nucleus Media); (4) schedule and track follow-up appointments; (5) connect with their clinicians; and (6) store health information.

Apple Watch integration allowed participants to monitor their heart rate and physical activity, receive reminders for medications and appointments (also delivered on the iPhone home screen), and track medications. The wireless blood pressure monitor integration allowed participants to track and review blood pressure recordings within the DHI.
was no monitoring of real-time data by the study or the patient’s clinical team. At this stage, the DHI was exclusively a self-management tool for patients.

The primary results of the MiCORE study have been published previously. At baseline, patients in the DHI group differed significantly from the historical control group on a number of sociodemographic, clinical, and hospitalization characteristics. Patients in the DHI group were younger, more likely to be male, more likely to have private insurance, and had a lower comorbidity burden, which was accounted for by using a propensity score.

**Model Development**

We developed a Markov model to evaluate the cost-effectiveness of the DHI plus standard of care versus standard of care alone in the 30-day discharge period after AMI from the US hospital perspective. A semi-Markov model of care provided through the intervention is advantageous over a decision tree because it can capture state transitions between different stages before and after an AMI event and death within the acute care setting. The model was run for 12 months in 30-day cycles. Our model was informed by data from the literature on post-AMI outcomes as well as from outcomes documented in the historical control group (Table 1). Four authors (V.B., S.L., J.Y., and D.M.) had full access to all data in the study and take responsibility for its integrity and data analysis.

Ten thousand simulated patients were followed as they transitioned through a series of health states during the 30-day postdischarge period after AMI (Fig. 1), with a probability associated with each transition state. These probabilities were derived from the literature about postdischarge outcomes for AMI (Tables 1, 2). During this period, patients were at risk for readmission either due to recurrent AMI or due to other disease states (eg, pneumonia). If none of these events occurred, patients remained in a “stable outpatient” state. The simulated patients were followed in the model either until their death or for 1 year. Transition probabilities were used to generate the series of states in which the simulated individuals would be found; then, costs and QALYs were summed.

**Population of Model Transition Parameters**

For the control arm, we obtained rates of post-AMI events (ie, readmission for recurrent AMI or other causes, or no complications state) and case fatality from the literature (Table 1). Additional readmission rates were obtained from the MiCORE study for both the DHI and historical control groups. The rate of all-cause readmission for participants in the DHI group was 6.5% (13/200) and 16.8% (145/864) among those in the historical control group. Of the 6.5% all-cause readmission in the DHI group, 38.5% were cardiac-related, and none were due to recurrent AMI. The model assumes unchanging efficacy and constant readmission rates.

**Effectiveness Measure**

We assigned a health utility weight (ie, QALYs) to each of the health states that reflected the preference for, or desirability of, that particular health state (Table 3). We used contingent market valuation techniques in determining our effectiveness measure. Given the 1-year time horizon, the model does not consider a discount rate. All utility values were taken from studies that used standardized models (ie, the time trade-off or standard gamble techniques). The utility weight for AMI (0.725) was obtained by using EuroQOL (EQ-5D) index scores collected in the Alberta Provincial Project for Outcome Assessment in Coronary Heart Disease database. The utility for post-AMI without complications was similarly obtained from EQ-5D scores and time trade-off techniques. We considered utility weights for readmission due to recurrent AMI or due to another complication separately. The utility value for readmission due to recurrent AMI (0.81) was obtained from a study in which individuals were assigned a specific index, or utility value, for the time they spent in a health state, measured using the EQ-5D instrument. For readmission due to other complications, we interpreted a utility value based on data (0.68) from a study that used time trade-off and contingent valuation techniques.

**TABLE 1. Probabilities Associated With Each Transition State**

| Probability | Base-case Estimate |
|-------------|-------------------|
| Death due to AMI | 0.236 |
| Recurrent MI | 0.089 |
| Death due to recurrent MI | 0.297 |
| Death due to non-MI complications | 0.012 |
| Readmission due to recurrent MI (with Corrie) | 0.02 |
| Readmission due to non-MI complications (with Corrie) | 0.03 |
| Recovery after recurrent MI | 0.87 |
| Recovery after recurrent MI (with Corrie) | 0.87 |

AMI indicates acute myocardial infarction; MI, myocardial infarction.

**TABLE 2. Utility Values for Each Health State**

| Parameters | Base-case Estimate | Sensitivity Analysis Range Tested |
|------------|-------------------|----------------------------------|
| AMI | 0.725 | 0.3–0.96 |
| No complications | 0.93 | 0.41–0.97 |
| Readmission due to MI | 0.81 | 0.34–0.82 |
| Readmission due to non-MI | 0.68 | 0.47–0.84 |

AMI indicates acute myocardial infarction; MI, myocardial infarction.
Cost Information

We focused on hospital costs for unplanned 30-day readmissions (Table 3). To generate a value proposition for the DHI, we developed a threshold analysis to determine the cost-savings that the DHI may accrue. We estimated typical costs associated with readmissions or death of AMI patients discharged with standard practices using 2014 US hospital costs from the Agency for Healthcare Research and Quality (AHRQ), and these values ranged from $17,600 for readmission due to recurrent AMI to $20,800 for the cost of AMI health state.29–31 We used the HCUPnet tool to generate the cost of each transition state.32 All cost data were then inflated to match 2019 US dollars using the general Consumer Price Index Inflation Calculator from the Bureau of Labor and Statistics.33

Cost-effectiveness and Sensitivity Analyses

We calculated the incremental cost-effectiveness ratio (ICER) of using the DHI plus standard of care compared with standard of care alone over the simulated 1-year study period. The willingness-to-pay threshold to determine acceptable cost-effectiveness was set at $100,000 per QALY.34 Means and 95% confidence intervals were calculated using 10,000 model iterations. To assess model robustness, we performed extensive deterministic sensitivity analyses. We used 50%–200% of the base-case estimates to perform 1-way sensitivity analyses of all input parameters (probability of AMI, recurrent AMI, readmission due to other complications, mortality, utilities, and costs of post-AMI events). Two-way sensitivity analyses were performed by simultaneously altering the costs, utilities, and probabilities. We also conducted a probabilistic sensitivity analysis, in which the model was run using a value of each parameter drawn randomly from the distribution assigned to that parameter. We used beta distributions for probabilities and gamma distributions for costs and utility decrements.

Budget Impact Analysis

The budget impact of adopting the DHI across the Johns Hopkins hospital was calculated over the total population enrolled in a Johns Hopkins Healthcare managed care plan, which was 429,000 in 2017.35 The budget impact model considered the impact on the Johns Hopkins hospital budget of adopting the DHI compared with a scenario where the standard of care was maintained. A 1-year time horizon was assumed. The total budget impact was calculated by looking at the cost per patient from our Markov model multiplied by the number of hospitalizations under both standard of care and in a scenario where the DHI was adopted. The net impact was determined by dividing the overall cost-savings by the total number of payors into the Johns Hopkins Healthcare managed care plan.

RESULTS

Cost-effectiveness of Corrie

Compared with standard of care alone, DHI use in addition to standard of care in patients hospitalized for AMI improved quality-adjusted survival by 0.80 QALYs and reduced costs by $10,024 per patient (Table 3) principally through the reduction in readmissions. Given that the DHI yielded greater health benefits at a lower cost over the full 1-year time horizon observed, the DHI was the dominant option over standard of care alone. The DHI was cost-saving compared with standard of care in 99.926% of the simulations and was cost-effective at a conventional willingness-to-pay threshold of $100,000/QALY gained in 99.7% of simulations, with a dominant ICER (Fig. 2). Overall, our results show that the DHI improves the lives of patients at a lower cost than the standard of care.

### TABLE 3. Expected Results of the Cost-effectiveness Analysis Comparing Prevention to Standard of Care for Corrie

| Intervention          | Cost ($) | Incremental Cost | Effectiveness (QALYs) | Incremental Effectiveness | ICER ($/QALY) |
|-----------------------|----------|------------------|-----------------------|--------------------------|---------------|
| Corrie                | 17,195   | 7.88             |                       |                          |               |
| Standard of care      | 27,940   | 10,024           | 7.08                  | −0.80                    | Dominated     |

ICER indicates incremental cost-effectiveness ratio; QALY, quality-adjusted life year.
Sensitivity Analysis

Univariate sensitivity analyses indicated that the DHI always dominated the standard of care. Two-way sensitivity analyses also maintained the dominance of the DHI over the standard of care. Even at the highest risk of recurrent AMI or other readmission causes with the DHI compared with standard of care, and with the lowest bound of spending on recurrent AMI or other readmission causes under standard of care, the DHI was still the preferred option at a conventional willingness-to-pay threshold of $100,000/QALY.

Cost Analysis

From our model, we calculated that the health benefits achieved from the DHI were at least as high as those achieved among patients who received standard of care, at ~$10,000 less per patient. However, this figure does not include the implementation costs of the DHI. Although the MiCORE study provided loaner iPhones to patients who did not own a Corrie compatible iOS device, we determined that enabling all patients to download Corrie onto their own phones would allow for greater impact and avoid the need to purchase devices. To facilitate this, we have developed an Android version of Corrie. Thus, we based our cost analysis on the assumption that patients will be using their own devices.

The cost of Corrie was estimated to be $229 per month per patient for a 1-year use term ($2750 per year). Based on this cost estimate, the use of the DHI leads to a cost-savings of $7274 per patient compared with standard of care alone (ie, $10,024 − $2750 = $7274). The $2750 figure is composed of a: (1) Bluetooth blood pressure monitor (~$40); (2) refurbished smartwatch (~$250); (3) medication pillbox (~$10); (4) tote bag (~$12.50); (5) printed instructions (~$5); and (6) clinical support for onboarding and maintenance of platform by engineering inclusive of server storage fees and helpline access per user (~$2432 annually). A full inventory of costs analyzed in this study is presented in Supplemental Digital Content 1 (http://links.lww.com/MLR/C324).

DISCUSSION

Principal Findings

DHIs are an innovative solution that demonstrate promise to improve outcomes and control costs by enabling improved patient monitoring, communication, and self-management. Using data from the MiCORE study as well as from the literature, we have demonstrated that this DHI appears to provide better outcomes (ie, greater effectiveness or QALYs) with the lowest bound of spending on recurrent AMI and other complications (for the most sensitive parameters used in the model). The cost-savings calculated in this study were specific to the costs saved by a payor (ie, hospital and insurance company). Accounting for the estimated cost of Corrie, the cost-savings per QALY per patient is $7274 compared with the standard of care alone. This study did not account for potential costs saved by the patient or society, such as through prevented missed days of work and out-of-pocket medical costs. It is possible that the DHI may demonstrate additional cost-saving potential from those perspectives. Based on the results of our study, it appears that the DHI is cost-saving (ie, the cost of deploying the DHI vs. using the standard of care alone), provides better outcomes (ie, greater effectiveness or QALYs), and the results are robust to examinations of uncertainty in the model’s assumptions.

Budget Impact Analysis

Based on the national estimated risk for AMI, we estimated that 9.5% of (107,000) inpatient visits recorded annually were AMI-related admissions. The total cost of hospitalizations at the standard of care cost was estimated to be ~$284 million per year. The total cost of hospitalizations with the DHI is ~$182 million per year. This represents a net budget impact of ~$101.9 million or a 36% financial saving to the hospital-managed care plan (Supplemental Digital Content 2, http://links.lww.com/MLR/C323). Considering that there were 429,000 individuals enrolled in the Johns Hopkins Healthcare managed care plan, this works out to a lowering of costs of $236 per individual annually ($101.9 million/429,000) covered by the plan.

The adoption of Corrie in AMI care could lower the average amount paid by each individual member into his/her Johns Hopkins Hospital-managed care plan by $236 per year, based on data from this study with consideration of all members of the plan (both those who have had an AMI and used the DHI and those who have not). Therefore, by reducing the overall cost of hospitalization and the number of hospitalizations, cost-savings could be realized by managed care plans and passed on to the individual members of the plan. However, further analysis would be needed to determine the specific cost-savings that would be accrued to the individual payor. The figures given here are simply indicative of potential cost-savings to the insurance scheme.

Comparison to Prior Literature

While there is a lack of prior cost-effectiveness studies of smartphone-based DHIs for CVD, the addition of digital telemedicine components to a cardiac rehabilitation program in Belgium has been shown to reduce readmissions and be cost-effective with an ICER of €21,707/QALY (~$24,033 US dollars). In the United States, patients often do not enter cardiac rehabilitation until weeks after hospital discharge, if at all, creating a need for the immediate postdischarge guidance that Corrie provides. The reduction in cost/QALY, as well as the overall reduction in recurrent AMI and all-cause readmission reported in MiCORE, imply that there is justification for using Corrie to enhance existing post-AMI care.

As payers continue to transition to value-based models, the desirability of DHIs for health systems is increasing. For
example, recent studies suggest that HRRP may be associated with fewer readmissions but may also be associated with increased mortality during the 30-day postdischarge period for some patients. This indicates that focus on a common value-based metric, reduced readmissions, may unintentionally result in poor outcomes for some patients. A DHI like Corrie can improve monitoring and support of patients during the critical postdischarge period, providing value to health care professionals, hospital systems, and patients alike. Our analysis indicates that the DHI not only has potential to support health system cost-savings and success in value-based payment models but that it can also serve as a valuable resource for patients in their recovery. Although the study is focused on Corrie in AMI recovery, we believe the analysis has broader implications for transitions of care and home-based care models.

Limitations, Strengths, and Future Directions

The risk of recurrent AMI within the DHI group is currently noted as being zero due to no readmissions due to AMI. However, these are unadjusted figures and do not necessarily reflect the risk in the general population of post-AMI patients. While the MiCORE study used propensity scores to ensure a balanced distribution of measured confounding variables at baseline between the DHI and historical control groups and also provides strong data on real-world effectiveness, a randomized controlled trial would provide more definitive efficacy data. Furthermore, the sample size of 200 AMI patients in the DHI group could pose a limitation; however, sufficient power was achieved in the MiCORE study to compare 30-day readmissions between the DHI and control group. In addition, while the budget impact analysis offers an initial assessment beyond the focused hospital perspective, future studies should attempt to evaluate the cost-effectiveness of DHIs from a more comprehensive societal perspective.

Furthermore, it should be noted that most of the MiCORE participants were admitted to 2 hospitals in Maryland, which operate under an all-payer global budget system, which incentivizes hospitals to reduce readmissions. Even so, 2018 reports from the Centers for Medicare and Medicaid Services and other investigators demonstrate no appreciable differences in 30-day readmission rates for all inpatient admissions between Maryland hospitals and matched control groups, so Maryland’s unique health economics should not substantially impact the external validity of our results.

While DHIs like Corrie Health offer a noninvasive mechanism to reduce readmissions, making them available to all patients entails additional complexity and resources. Transitioning this research to routine practice will require consideration of the costs associated with study personnel, liability insurance, data maintenance, and security measures. Additional costs may be required to make a resource like Corrie available to patients with sensory impairments or cognitive decline. These costs should all be factored in when computing an overall ICER that accounts for wider costs.

The benefits of Corrie may not be uniformly experienced by the target patient population, particularly by older adults. Selection bias may hinder the generalizability of these results. Ultimately, only 22% of eligible inpatients were enrolled in the DHI group in the MiCORE study, which is similar to another inpatient DHI study with an enrollment rate of 14%. The majority of patients were excluded from the DHI group because they did not own a smartphone. Yet, the DHI group was still a diverse sample with a mean age of 59.2 years (SD: 11.5 y), 29% women, 29% non-White, and a median household income of $70,000. The median household income in the DHI group was similar to the US Census 2015–2019 American Community Survey which estimated household income at $62,843.4

A future step would be to incorporate features that make the DHI accessible to a wider population, regardless of education or income levels. Nevertheless, 71% of low-income adults and 53% of adults aged 65 and older in the United States own a smartphone. Among low-income adults, 26% are dependent on smartphones for internet access. Thus, DHIs have the potential to expand access to care. In an analysis from the MiCORE study, it was found that age, sex, and race were not significantly associated with DHI use even after adjusting for a number of covariates. Thus, DHIs may have a role in improving health equity. Cost-effective interventions that are potentially reimbursable by Medicare/Medicaid may have a particular impact among underserved populations. Finally, although Corrie was available only on iOS devices during the MiCORE study, we provided “loaner” iPhones to patients with other types of smartphones. This allowed us to recruit a more socioeconomically diverse sample and mitigate selection bias.

Sustainability

There are a number of factors that need to be considered for the long-term success of the program. In the research environment, MiCORE study team members identified potential participants through the electronic medical record, delivered the DHI to patients, educated patients on technology use, and acted as tech support if needed. The future success of the program will depend upon the integration of the DHI into clinical practice. Instead of study team members, this could be done through a transitional care navigator or an automatic electronic medical record feature to identify eligible patients and send a message to download the DHI. Then the patients and their family could use short videos that guide the setup process. From that point, intervention fidelity is crucial, and future research could assess the role of a clinician portal and automated reminders generated from real-time patient data to increase interactivity and feedback and patient engagement. Ultimately, long-term clinical adoption of the program will likely depend upon how well the technology can be integrated into the usual care pathway.

CONCLUSION

The current results, among the first to systematically evaluate the cost-effectiveness of a DHI specific to CVD, suggest that DHIs have significant potential to enhance standard treatments while cutting costs associated with post-MI treatment.

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REFERENCES
1. Epstein AM, Jha AK, Orav EJ. The relationship between hospital admission rates and rehospitalizations. N Engl J Med. 2011;365:2287–2295.
2. Medicare Payment Advisory Commission. Report to the Congress: Promoting Greater Efficiency in Medicare. Washington, DC: Medicare Payment Advisory Commission; 2007.
3. Catalyst New England Journal of Medicine. Hospital readmissions reduction program (HRRP); 2018. Available at: https://catalyst.nejm.org/hospital-readmissions-reduction-program-hrrp/. Accessed August 25, 2020.
4. Fingar K, Washington R. Trends in hospital readmissions for four high-volume conditions, 2009–2013: HCUP Statistical Brief #196. Rockville, MD: Agency for Healthcare Research and Quality; 2015. Available at: http://www.hcup-us.ahrq.gov/reports/statbriefs/sb196-Readmissions-Trends-High-Volume-Conditions.pdf.
5. Yale New Haven Health Services Corporation Center for Outcomes Research and Evaluation. Medicare hospital quality chartbook: Variation in 30-day readmission rates across hospitals following hospitalization for acute myocardial infarction; September 2015. Available at: www.cmsospitaltchalchartbook/file1/114/download?token=Lux09FSZ. Accessed August 25, 2020.
6. Dharmarajan K, Hsieh AF, Lin Z, et al. Diagnoses and timing of 30-day readmissions after hospitalization for heart failure, acute myocardial infarction, or pneumonia. JAMA. 2013;309:355–363.
7. Widmer RJ, Collins NM, Collins CS, et al. Digital health interventions for the prevention of cardiovascular disease: a systematic review and meta-analysis. Mayo Clin Proc. 2015;90:469–480.
8. de la Torre-Diez I, López-Coronado M, Vaca C, et al. Cost-utility and cost-effectiveness studies of telemedicine, electronic, and mobile health systems in the literature: a systematic review. Telemed J E Health. 2015;21:81–85.
9. Frederix I, Hansen D, Coninx K, et al. Effect of comprehensive cardiac telerehabilitation on one-year cardiovascular rehospitalization rate, medical costs, and quality of life: a cost-effectiveness analysis. Eur J Prev Cardiol. 2016;23:674–682.
10. Krishnan A, Finkelstein EA, Levine E, et al. A digital behavioral weight gain prevention intervention in primary care practice: cost and cost-effectiveness analysis. J Med Internet Res. 2019;21:e12201.
11. Marvel FA, Wang J, Martin SS. Digital health innovation: a toolkit to navigate from concept to clinical testing. J MRD Cardio. 2018;2:e2.
12. US National Library of Medicine. Myocardial infarction, Combined-device, recovery enhancement study (MiCORE); 2018. Available at: https://clinicaltrials.gov/ct2/show/NCT03760796. Accessed August 25, 2020.
13. Spaulding EM, Marvel FA, Lee MA, et al. Corrie health digital platform for self-management in secondary prevention after acute myocardial infarction. Circ Cardiovasc Qual Outcomes. 2019;12:e005509.
14. Yang WE, Spaulding EM, Lumelsky D, et al. Strategies for the successful implementation of a novel iPhone loaner system (iShare) in mHealth interventions: prospective study. JMIR Mhealth Uhealth. 2019;7:e16391.
15. Rosenstock IM. Historical origins of the health belief model. Health Educ Monogr. 1974;2:328–335.
16. Bandura A. Social Foundations of Thought and Action: A Social Cognitive Theory. Englewood Cliffs, NJ: Prentice-Hall Inc.; 1986.
17. Marvel FA, Spaulding EM, Lee MA, et al. A digital health intervention in acute myocardial infarction. Circ Cardiovasc Qual Outcomes. 2021;14:e007741.
18. Olarui E, Cadwell KK, Hancock E, et al. Current recommendations on the estimation of transition probabilities in markov cohort models for use in health care decision-making: a targeted literature review. Clinicoecon Outcomes Res. 2017;9:537–549.
19. Briggs A, Claxton K. Decision Modeling for Health Economics (Handbook in Health Economic Evaluation). Great Clarendon Street, Oxford: Oxford University Press; 2006.
20. Brown TM, Deng L, Becker DJ, et al. Trends in mortality and recurrent coronary heart disease events after an acute myocardial infarction among Medicare beneficiaries, 2001–2009. Am Heart J. 2015;170:249–255.
21. Chaudhry SI, Khan RF, Chen J, et al. National trends in recurrent AMI hospitalizations 1 year after acute myocardial infarction in Medicare beneficiaries: 1999–2010. J Am Heart Assoc. 2013;4:e001197.
22. Krumholz HM, Hsieh A, Dreyer RP, et al. Trajectories of risk for specific readmission diagnoses after hospitalization for heart failure, acute myocardial infarction, or pneumonia. PLoS One. 2016;11:e0160492.
23. Galper BZ, Wang YC, Einstein AJ. Strategies for primary prevention of coronary heart disease based on risk stratification by the ACC/AHA lipid guidelines, ATP III guidelines, coronary calcium-determination, and C-reactive protein, and a global treat-all-strategy: a comparative-effectiveness modeling study. PLoS One. 2015;10:e0138092.
24. Liew D, De Abreu Lourenço R, Adena M, et al. Cost-effectiveness of 12-month treatment with ticagrelor compared with clopidogrel in the management of acute coronary syndromes. Clin Ther. 2013;35:1110.e9–1117.e9.
25. Priest VL, Scuffham PA, Hachamovitch R, et al. Cost-effectiveness of coronary computed tomography and cardiac stress imaging in the emergency department: a decision analytic model comparing diagnostic strategies for chest pain in patients at low risk of acute coronary syndromes. JACC Cardiovasc Imaging. 2011;4:549–556.
26. Torrance GW. Utility approach to measuring health-related quality of life. J Chronic Dis. 1987;40:593–600.
27. Ghali WA, Knudson ML. Overview of the alberta provincial project for outcome assessment in coronary heart disease. on behalf of the APPROACH investigators. Can J Cardiol. 2000;16:1225–1230.
28. Lee GM, Saloman JA, LeBaron CW, et al. Health-state valuations for pertussis: methods for valuing short-term health states. Health Qual Life Outcomes. 2005;3:17.
29. Fingar KR, Barrett ML, Jiang HI. A comparison of all-cause 7-day and 30-day readmissions, 2014: HCUP statistical brief #230. Rockville, MD: Agency for Healthcare Research and Quality (US); 2017. Available at: www.hcup-us.ahrq.gov/reports/statbriefs/sb230-7-Day-Versus-30-Day-Readmissions.pdf.
30. Hines AL, Barrett ML, Jiang HI, et al. Conditions with the largest number of adult hospital readmissions by payer, 2011: HCUP statistical brief #817. Rockville, MD: Agency for Healthcare Research and Quality (US); 2014. Available at: http://www.hcup-us.ahrq.gov/reports/statbriefs/sb817-Conditions-Readmissions-Payer.pdf.
31. Noset-Metzger Q, Bierman AS, Borsky A, et al. Coronary artery disease, acute myocardial infarction, and ischemic stroke rates among inpatient stays, 2001–2014: HCUP statistical brief #241. Rockville, MD: Agency for Healthcare Research and Quality (US); 2018. Available at: www.hcup-us.ahrq.gov/reports/statbriefs/sb241-Coronary-Artery-AMI-Stroke-Hospital-Stays-2001-2014.pdf.
32. US Department of Health & Human Services, Agency for Healthcare Research and Quality. Myocardial infarction, Combined-device, recovery enhancement study (MiCORE); 2018. Available at: https://clinicaltrials.gov/ct2/show/NCT03760796. Accessed August 25, 2020.
33. United States Bureau of Labor Statistics. CPI inflation calculator. 2021. Available at: www.bls.gov/data/inflation_calculator.htm. Accessed August 25, 2020.

34. Sanders GD, Neumann PJ, Basu A, et al. Recommendations for conduct, methodological practices, and reporting of cost-effectiveness analyses: second panel on cost-effectiveness in health and medicine. *JAMA*. 2016;316:1093–1103.

35. Johns Hopkins Medicine. Johns Hopkins Medicine, headquartered in Baltimore, Maryland, is an $8 billion integrated global health enterprise and one of the leading health care systems in the United States; 2018. Available at: https://www.hopkinsmedicine.org/about_downloads/JHM-Fast-Facts.pdf. Accessed August 25, 2020.

36. Benjamin E, Blaha M, Chiuve S, et al. Heart disease and stroke Statistics—2017 update: a report from the American Heart Association. *Circulation*. 2017;135:e146–e603.

37. Cleghorn C, Wilson N, Nair N, et al. Health benefits and cost-effectiveness from promoting smartphone apps for weight loss: multistate life table modeling. *JMIR Mhealth Uhealth*. 2019;7:e11118.

38. Rinaldi G, Hijazi A, Haghparast-Bidgoli H. Cost and cost-effectiveness of mHealth interventions for the prevention and control of type 2 diabetes mellitus: a protocol for a systematic review. *BMJ Open*. 2019;9:e027490.

39. Sjöström M, Lindholm L, Samuelsson E. Mobile app for treatment of stress urinary incontinence: a cost-effectiveness analysis. *J Med Internet Res*. 2017;19:e154.

40. Ritchey MD, Maresh S, McNeely J, et al. Tracking cardiac rehabilitation participation and completion among medicare beneficiaries to inform the efforts of a national initiative. *Circ Cardiovasc Qual Outcomes*. 2020;13:e005902.

41. Wadhera RK, Joynt Maddox KE, Wasfy JH, et al. Association of the hospital readmissions reduction program with mortality among medicare beneficiaries hospitalized for heart failure, acute myocardial infarction, and pneumonia. *JAMA*. 2018;320:2542–2552.

42. Roberts ET, McWilliams JM, Hatfield LA, et al. Changes in health care use associated with the introduction of hospital global budgets in Maryland. *JAMA Intern Med*. 2018;178:260–268.

43. Haber S, Beil H, Amico P, et al. *Evaluation of the Maryland all-payer Model: Third Annual Report*. Waltham, MA: RTI International; 2018.

44. Patel MS, Polsky D, Kennedy EH, et al. Smartphones vs wearable devices for remotely monitoring physical activity after hospital discharge: a secondary analysis of a randomized clinical trial. *JAMA Neurol*. 2020;7:e1920677.

45. United States Census Bureau. Household income. 2020. Available at: www.census.gov/search-results.html?q=household+income&page=1&stategeo=none&searchtype=web&cssp=SERP&charset=UTF-8. Accessed May 5, 2021.

46. Pew Research Center. Mobile technology fact sheet. Pew Research Center’s Internet & American Life Project; 2019. Available at: www.pewinternet.org/fact-sheets/mobile-technology-fact-sheet/. Accessed August 25, 2020.

47. Shah LM, Ding J, Spaulding EM, et al. Sociodemographic characteristics predicting digital health intervention use after acute myocardial infarction. *J Cardiovasc Transl Res*. [published online ahead of print May 17, 2021]. doi: 10.1007/s12265-021-10098-9.