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The value of remote monitoring systems for treatment of chronic disease

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Caring for patients with chronic illnesses is costly—75% of U.S. healthcare spending can be attributed to treating chronic conditions (CDC, 2009a,b). Several components contribute to the cost of treating chronic disease. There are the direct costs associated with treating the disease, and those associated with complications that arise as a result of the disease. There are also indirect costs associated with loss of productivity and quality of life. Technological advances in remote monitoring systems (RMS) may provide a more cost-effective and less labor-intensive way to manage chronic disease by focusing on preventive measures and continuous monitoring instead of emergency care and hospital admissions. In this paper, we develop a model that estimates the total potential savings associated with broad introduction of RMS, and considers how capacity constraints and fairness concerns should impact RMS allocation to target populations. To illustrate the value and insight the model may provide, we conduct a small computational study that focuses on direct costs that would be real costs to a healthcare provider or payer for a subset of the most common chronic diseases: diabetes, heart failure, and hypertension. The computational study shows that, under reasonable assumptions, broad introduction of RMS will lead to substantial cost savings for target populations. The study provides proof of concept that the model could serve as a useful tool for policy makers, as it allows a decision maker to modify cost, risk, and capacity parameters to determine reasonable policies for the allocation of and reimbursement for RMS.

Keywords: Telehealth, telemedicine, operations research, optimization, chronic disease

1. Introduction

Caring for patients with chronic illnesses is costly—75% of U.S. healthcare spending can be attributed to treating chronic conditions (CDC, 2009b). Nearly half of all American adults have been diagnosed with at least one chronic disease (CDC, 2009b), and the number of people living with chronic illnesses is expected to increase. As evidence, the percent of adults diagnosed with diabetes almost doubled from 5.1% in 1997 to 9% in 2009 (CDC, 2009a). Additionally, the risk for chronic disease increases with age, and by 2040, the number of people aged 65 and older is expected to double and the number of people aged 85 and older is expected to quadruple (Ortman and Guarneri, 2009). Technological advances in remote monitoring systems (RMS) may provide a more cost-effective and less labor-intensive way to manage the care of patients with chronic illnesses by focusing on preventive measures and continuous monitoring instead of emergency care and hospital admissions. In this paper, we develop a model that estimates the potential cost savings associated with using RMS in the treatment of the growing population of chronically ill persons.

Several components contribute to the cost of treating chronic disease. First, there are the direct costs associated with treating the disease. This can include, among other things, the direct cost of visits to and consultations with caregivers, the cost of medications, and the cost of screenings and other diagnostic and health monitoring procedures. Second, there are the costs associated with complications that may arise as a result of the disease, such as hospitalizations and emergency room visits. Third, there are the indirect costs associated with the loss of productivity due to the above treatments, screenings, and complications (e.g., time spent visiting clinics and hospitals). Finally, there is also the impact that the illness has on quality of life, though these costs are often difficult to quantify.

Several studies have examined the effectiveness of RMS for the treatment of chronic disease. These primarily focus

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on diabetes, cardiovascular disease, and pulmonary disease. For diabetes, Leichter *et al.* (2013) found from a randomized controlled study that a telemedicine-based treatment protocol in diabetes patients yields similar clinical outcomes compared with traditional, clinic-based protocols. They conclude that remote monitoring can therefore expand access at reduced costs.

For cardiac patients, Chaudhry *et al.* (2007) examined the impact of RMS on patients with cardiac heart failure and found the evidence base too limited. Klersy *et al.* (2009), however, found that for patients with heart failure the use of RMS was associated with several positive outcomes including lower number of deaths and fewer hospitalizations when compared to a control.

Jaana *et al.* (2009) performed a systematic review of 23 studies and found that for respiratory conditions RMS had a positive effect on patient behavior and on early identification of deterioration in patient conditions. They argue that the magnitude of these effects, however, is preliminary. McKinstry (2009) stated that although RMS shows promise for chronic obstructive pulmonary disease (COPD), the interventions have to this point been complex. Paré *et al.* (2007) performed a systematic review of 65 empirical studies and found that telemonitoring had more consistent improvement in clinical outcomes for pulmonary and cardiac conditions than for diabetes and hypertension. However, they cited that very few in-depth cost analyses were performed.

Some studies have also examined the impact of RMS on target populations. For example, Darkins *et al.* (2009) examined the impact of a remote telemedicine program on a cohort of over 17,000 veterans. Results showed a reduction of 25% in number of bed days, a reduction of 19% of hospital emissions, and a self-reported satisfaction score by patients of the program of 86%. The per patient annual cost of implementing the program was $1,600. Baker *et al.* (2013) studied an RMS program for Medicare beneficiaries. They found that after two years in the program, participants have 15% lower mortality and 18% fewer inpatient admissions than the control. They did not find an impact on ED admissions, however. They found the biggest effect was for those with COPD and congestive heart failure.

Remote monitoring systems have the potential to lower the costs associated with treating chronic disease. Using RMS, disease-specific patient health indicators are collected from biomedical devices used by patients in their homes, and the data is transmitted to a remote server for examination and follow-up by healthcare providers. This enables earlier health interventions when unusual readings are detected. Additionally, RMS facilitates patient adherence to daily disease management guidelines by sending patient reminders, providing education, and enabling communication with caregivers via tools such as videoconferencing. By involving patients in the daily management of their health and by enabling earlier healthcare provider interventions, the expected frequency of occurrence of costly complications is reduced. Direct and indirect costs of treating the disease are also potentially reduced via RMS, as consultations with caregivers and health monitoring procedures are performed remotely.

Recent clinical research has supported the hypotheses that increased adherence to disease management guidelines can reduce the occurrence of serious complications, and that RMS are more effective than traditional care in encouraging patient adherence. A critical review of 16 heart failure (HF) disease management studies found that all reported reduced hospitalizations, improved quality of life and compliance with diet and medication recommendations (Rich, 1999). The studies which included cost-benefit analyses of the disease management programs all found the programs to be cost-effective. In another study conducted by Intel and Aetna, 164 out of 315 Medicare patients suffering from HF were able to avoid some hospital stays as a result of their use of a remote health management system (Horowitz, 2010). Furthermore, in a survey conducted by Fazzi Associates and Philips regarding the impact of the use of telehealth in the home care industry, 49.7% of responding home care agencies reported a decrease in the number of home health visits per patient, 76.6% reported a decrease in unplanned hospitalizations, and 88.6% reported an increase in quality outcomes (Fazzi Associates, 2008).

The goal of this paper is to analyze the total savings potential of RMS. Such analysis could guide reimbursement policies for health insurance providers that may be reluctant to pay for these services. A survey of healthcare decision makers conducted by Intel revealed that 87% of respondents believe telehealth will transform healthcare in the next 10 years, but the top barrier to implementation was identified as reimbursement (Burt, 2010). We develop a model that estimates the value of providing RMS to target populations, and determines which population groups should receive systems when capacity is limited. The model can also determine an equitable allocation of systems that distributes the benefits associated with RMS use fairly across population groups. The model is flexible and can easily accommodate different levels of detail, in terms of disease categories and use options and benefit characteristics of the systems.

To illustrate and demonstrate the value and insight the model may provide, we have conducted a computational study from the perspective of a healthcare provider or payer. In it, we consider a small subset of the most common chronic illnesses: diabetes, heart failure, and hypertension. We focus on the direct costs to a provider or payer, and do not include the indirect costs associated with a loss of productivity and/or quality of life. The computational study shows that, under reasonable assumptions, the broad introduction of RMS will lead to substantial cost savings for target populations. The estimated savings are 13% when monitoring capacity is unlimited and 6% when a reasonable constraint is placed on capacity. When equity is considered and benefits are distributed fairly across population groups, estimated savings are 5.4%. Even in the least optimistic scenario examined, estimated savings are 1.33%, or approximately $3.9 billion dollars annually. It should be noted that the savings reported are quite conservative, as indirect costs are not included in the computational study.

The primary contributions of this paper are threefold. First, the model we develop estimates the total potential savings associated with broad introduction of RMS, and considers how capacity constraints and fairness concerns should impact RMS allocation to target populations. The clinical research we have discussed has demonstrated savings for individual population classes, but no research of which we are aware has considered interactions between various cost components and disease groups. Second, we present a comprehensive set of data that can be used to estimate total savings potential associated with RMS for three of the most common chronic diseases. Building this database required extensive review of clinical literature, and it will serve as a useful resource for other researchers analyzing chronic disease costs and risks. Finally, our model could serve as a useful tool for policy makers, as it allows a decision maker to modify cost, risk, and capacity parameters to determine reasonable policies for the allocation of and reimbursement for RMS.

The remainder of the paper is organized as follows. In Section 2, we describe the current state of the RMS market. In Section 3, we introduce the models we propose for assessing the total potential savings of RMS. In Sections 4 and 5, we present the case study data and computational results. Finally, in Section 6, we elaborate on conclusions and future research.

2. Remote monitoring system market

Monitoring systems on the market today are laptop-like units that have the capability to connect to wired and wireless medical devices such as blood pressure monitors, glucose meters, pulse oximeters, scales, and peak flow meters. They can be configured to collect vital signs and transmit results to healthcare providers for monitoring. They include communication tools such as video conferencing and email notification, and can also send patient reminders and facilitate patient education. Patients interact with the systems according to scripted content based on specific patient diagnoses. Two popular systems on the market are the Intel Health Guide and Bosch Health Buddy (Intel, 2010; Bosch Healthcare, 2010). Medical devices that communicate with mobile phones, and applications that support their use, are also being developed, eliminating the need for a stationary laptop-like unit. A recent development is an electronic skin platform, similar to a temporary tattoo, that has the ability to sense biometric indicators and communicate readings (Kim *et al.*, 2011).

Both healthcare decision makers and private industries are showing increased interest in these new technologies. A survey of healthcare decision makers conducted by Intel revealed that 67% of respondents were using some form of telehealth products, and 87% of those are satisfied with results. The benefits include improved patient outcomes, better doctor access to patient data, and early detection of health issues (Burt, 2010). In April 2009, Intel and GE announced an alliance to develop and market home-based health technologies to enable seniors to live at home independently and safely, and patients with chronic disease to manage their care from home (GE, 2010). The home-based technologies are intended to lower total healthcare costs by keeping patients out of hospitals. In August 2010, Intel and GE announced a joint venture that will combine assets from Intel's digital health group and GE Healthcare's home health division. The goal of the new company is to develop and market products, services, and technologies that promote healthy independent living at home and in assisted living communities. The market for such technologies is forecasted to more than double from $3 billion in 2009 to $7.7 billion in 2012 (King, 2010).

There have been a very limited number of economic studies of RMS in practice. Paré *et al.* (2013) measured healthcare services consumed by patients with various chronic diseases and found significant reductions in number of hospitalizations, length of average hospital stay, and number of emergency room visits, though the number of home visits by nurses increased. Polisena *et al.* (2009) found that from the perspective of an insurance provider, RMS produced cost savings, but also stated that the quality of the studies used in their analysis was in general quite low. Finally, Paré *et al.* (2006) compared the costs of patients with COPD with and without RMS. They found that over a 6-month period RMS saved $355 compared to the control, a 15% reduction in costs. This figure is in line with the 13% savings we found with unlimited RMS capacity.

Clinical studies are expensive to conduct, and the data is not always of high quality. The value of the work presented here is that we can study the impact of RMS *ex ante*. This allows us to consider factors such as targeting specific populations, untested technology, and equitability; these would not be possible to estimate from clinical methods.

3. Assessing the total savings potential of RMS

To introduce a model aimed at assessing the total savings potential of RMS, the concepts of population classes, treatment bundles, and procedures are defined.

Definition. *A population class is a group of patients that have similar recommended treatment guidelines and baseline risk for complications.*

Because patients at different stages of a disease typically require different treatment and may have different risk for complications, a separate population class is introduced for each stage of a disease (e.g., pre-diabetic and Type I or Type II diabetic). Furthermore, patients with co-morbidities (more than one disease) may also require specialized treatment plans, so a separate population class is introduced for each combination of diagnoses.

Definition. *A treatment bundle is a specific method for delivering the care specified by the treatment guidelines for a population class.*

Definition. *A procedure is care delivered in a treatment bundle.*

Examples of procedures include medical tests such as cholesterol and blood pressure screenings, as well as office visits, patient education, and patient reminders. Because some treatment bundles may include the option for more frequent health monitoring (e.g., continuous monitoring using RMS), we assume that a treatment bundle specifies the frequency with which procedures are performed. For example, a patient diagnosed with hypertension may be instructed to measure blood pressure at home once per day.

Associated with each procedure in each treatment bundle is a direct and indirect cost. Note that direct and indirect costs of treatment vary between treatment bundles for a given population class, because both procedure frequency and how a procedure is performed are determined by the treatment bundle employed. Additionally, risk for complications, thus expected cost of complications, may vary between treatment bundles for a given population class, because the effectiveness of the care delivered may vary.

To illustrate the concepts of population classes, treatment bundles, and procedures, consider a population class comprised of patients that have been diagnosed with heart failure. Patients with HF typically demonstrate high utilization of healthcare resources with frequent physician visits, hospitalizations, and trips to the emergency department. In 2008, Blue Cross Blue Shield of Michigan reported the condition-specific hospital spending for non-Medicare adults with HF as over $9000 per patient per year (Center for Healthcare Research and Transformation, 2010). The American Heart Association (2013a,b,c) recommended treatment guidelines for HF include lifestyle modifications such as smoking cessation, regular exercise, and a diet that is low in salt and free of alcohol. In addition, hypertension, lipid disorders, and metabolic syndrome should be treated and controlled, and medications such as diuretics and Beta-blockers should be prescribed. Finally, serum electrolytes, renal function, and weight should be monitored regularly (Jessup *et al.*, 2009). Table 1 describes two treatment bundles that meet the requirements for the HF population class.

Using the RMS bundle, lifestyle modifications and medication compliance reminders and education are procedures that occur on a daily basis, contrasted with occurring only at hospital discharge or during a doctor's office visit using the traditional bundle. Thus, the RMS bundle has the procedures: daily education, daily reminder, daily nurse notification of compliance, daily weight monitoring, weekly teleconference, etc. The traditional bundle has the procedures: quarterly doctor's visits, quarterly education and follow-up, quarterly weight monitoring, etc. Because procedures occur on a daily basis with the RMS bundle, patient adherence to disease management guidelines is expected to be better than with the traditional bundle. Additionally, timely health interventions are enabled when the RMS bundle is used to continuously monitor biometric indicators. Together, patient adherence and timely interventions lead to decreased risk for complications. Lower expected cost of complications associated with RMS-enabled increased effectiveness of care is a key element of the analysis performed in this paper.

The direct costs associated with procedures in the traditional bundle include the cost of doctor's visits and monitoring procedures performed during visits. The direct costs associated with procedures in the RMS bundle include the cost of the device itself, the cost of testing supplies used in conjunction with the device, and the cost of transmitting and monitoring the data. In the traditional bundle, indirect costs associated with loss of productivity include time required to drive to and from doctor's visit, wait for the visit to begin, and the duration of the visit. In the RMS bundle, this only includes time spent interacting with the system. Other types of indirect costs that could be incorporated in our model but are not captured in our computational study include, for example, improvements in quality adjusted life years (QALYs). These indirect costs are social costs, and important from a public health or government perspective. However, they would not be real costs to a provider, so we are conservative in how we report the savings potential of RMS.

Before introducing our model and computational study, it is important to note that our model is intended to serve as a proof of concept. The significance of our conclusions strongly depend on the quality of the analysis of the costs and benefits associated with RMS. Estimates taken from the clinical literature regarding the effectiveness of RMS in decreasing risk for costly complications are used to populate our model. Sensitivity analysis is embedded in our computational study to provide some protection against uncertainty in estimating the complication risk associated with each population class and treatment bundle. This will be discussed in detail in Section 4.

3.1. *Basic model*

The basic model formalizes the discussion concerning the computation of the costs associated with a monitoring bundle and primarily serves to introduce notation.

Data elements

$\mathcal{I}$:	set of population classes
n_i:	number of patients in population class $i \in \mathcal{I}$
$\mathcal{B}_i$:	set of available treatment bundles for class $i \in \mathcal{I}$
$\mathcal{B}$:	set of all treatment bundles, $\mathcal{B} = \bigcup_{i \in \mathcal{I}} \mathcal{B}_i$
m_b:	purchase, monitoring, and transmission cost of bundle b
$\mathcal{T}_b$:	set of procedures in bundle $b \in \mathcal{B}$
$\mathcal{T}$:	set of all procedures, $\mathcal{T} = \bigcup_{b \in \mathcal{B}} \mathcal{T}_b$
d_t:	direct cost of procedure $t \in \mathcal{T}$
l_t:	indirect cost of procedure $t \in \mathcal{T}$
f_t:	frequency of procedure $t \in \mathcal{T}$
$\mathcal{J}_b$:	set of complications associated with bundle $b \in \mathcal{B}$
$\mathcal{J}$:	set of all complications, $\mathcal{J} = \bigcup_{b \in \mathcal{B}} \mathcal{J}_b$
c_j:	cost of complication $j \in \mathcal{J}$
p_j:	probability of occurrence of complication $j \in \mathcal{J}$

Assume that $\mathcal{B}_i$, the set of available treatment bundles for population class i, includes two elements: $b = 0$ corresponding to the traditional healthcare delivery environment, and $b = 1$ corresponding to the remote monitoring system. Thus, the set of all bundles, $\mathcal{B}$, includes $2|\mathcal{I}|$ elements; 2 per population class. Note that the specific procedures and complications indicated by these two bundles for different population classes will be different, as the recommended monitoring procedures and their frequencies vary depending on diagnosis, as does risk for complications. Thus, the specific type of remote monitoring system indicated by $b = 1$ for different population classes will also be different, as different procedures require different types of hardware plug-ins (e.g., blood pressure cuff versus pulse oximeter) to the main system. The model can be easily extended to accommodate more than two treatment bundles for a population class, for example, a treatment bundle that combines the use of RMS with traditional, but fewer, doctor's visits.

Let C_i^b denote the total expected annual cost of treatment for a patient in population class i using bundle b. Note that m_b, the purchase, monitoring, and transmission cost of bundle b, will be equal to zero for the traditional bundle ($b = 0$) for all population classes, because the associated traditional healthcare delivery environment does not make use of RMS. Then, the total expected annual cost of treatment for a patient in population class i using bundle $b \in \mathcal{B}_i$ can be calculated as follows:

$$C_i^b = m_b + \sum_{t \in \mathcal{T}_b} f_t (d_t + l_t) + \sum_{j \in \mathcal{J}_b} c_j p_j. \tag{1}$$

Thus, the total annual expected cost of treatment for patient i using bundle b is the sum of purchase and monitoring costs, direct and indirect cost of procedures, and expected cost of complications. Let S_i denote the savings to a patient in population class i associated with using RMS. Given the above, S_i is simply

$$S_i = min\left(0, C_i^0 - C_i^1\right). \tag{2}$$

This represents the difference between the cost of a traditional treatment bundle and a treatment bundle involving the use of RMS. For a given population class, if it is more cost-effective to use the traditional bundle, no cost savings are credited. The total savings potential of using RMS across all population classes, S, is

$$S = \sum_{i \in \mathcal{I}} n_i S_i. \tag{3}$$

That is, we compute the savings per patient associated with switching from the traditional healthcare delivery environment to the remote monitoring system, and multiply by the number of patients in the class. Of course, the implicit assumption in this base model is that there are no limits on the number of RMS that may be assigned to patients.

3.2. *Capacitated model*

It is unrealistic to assume there will be unlimited RMS capacity. The number of patients that could be assigned RMS may be constrained by nurse capacity for data transmission monitoring and follow-up, or constrained by the number of physical devices available. Therefore, the next model assumes we know the number of RMS that may be assigned to patients. In this situation, the problem is not simply one of computing the minimum-cost treatment bundle for each population class, as we may not be able to provide the necessary bundles to each of the patients in the class. We do

Table 1. HF treatment bundles

Treatment component	Traditional bundle	RMS bundle
Lifestyle modifications and medication compliance	Instructions given during doctors visit and/or hospital discharge	Daily education and reminders on device, nurse notification of non-compliance
Observation and close follow-up	Doctor's visits	Teleconference/videoconference or doctor's visits
Potassium/renal function/weight monitoring	Doctor's visits	Biometric sensors collect data and transmit to server for review by nurse

assume that the combined capacity of the traditional and device bundles is adequate to treat every patient in each population class.

Note that we do not assume that all patients can be treated with a traditional bundle. There may not be sufficient capacity of doctors in the traditional system, or certain classes of patients may be unable to visit the doctor (e.g., homebound). By the introduction of RMS, we may be able to treat *more* patients. Future research could examine model variants where the number of patients that can be treated is maximized.

Data elements

r_k: amount of resource k
u_k^b: amount of resource k used in a single patient assignment of treatment bundle b

We have kept the model general by introducing the concept of resources. Resources in this situation could refer to manufactured devices, or to annual nurse-hours available for monitoring incoming data transmissions.

Decision variables

y_i^b: fraction of i^{th} population class served by monitoring bundle b

Objective function

$$minimize \sum_{i\in\mathcal{I}} \sum_{b\in\mathcal{B}_i} n_i C_i^b y_i^b \tag{4}$$

Constraints

$$\sum_{b\in\mathcal{B}_i} y_i^b = 1 \quad \forall\, i \in \mathcal{I}, \tag{5}$$

$$\sum_{i\in\mathcal{I}} \sum_{b\in\mathcal{B}_i} n_i u_k^b y_i^b \le r_k \quad \forall\, k, \tag{6}$$

$$0 \le y_i^b \le 1 \quad \forall\, i \in \mathcal{I},\ b \in \mathcal{B}_i. \tag{7}$$

Constraints (5) ensure that for each population class i, all patients are served by either the traditional or RMS bundle. Constraints (6) ensure that availability limits are respected. In this model, it is assumed that we are allowed to serve patients in the same population class with different bundles. As this introduces a distinction between patients within a population class, which could be considered an equitability concern, we may also consider the variant in which the decision variables are restricted to be binary, ensuring every patient in a population class receives the same bundle.

3.3. *Capacitated model with equitability*

The models discussed in Sections 3.1 and 3.2 are completely driven by economic considerations. When health is concerned, there are also social considerations, especially when treatment options impact quality of life. If RMS improves the quality of life of patients, then equity becomes a necessary consideration. One method for addressing equitability of RMS allocation to population classes when capacity is limited is to distribute the savings associated with RMS use fairly across population classes. Clearly the notion of what constitutes an equitable allocation of health resources is a much debated and difficult question and we take an admittedly simple, though pragmatic, view here. This model minimizes annual expected cost to serve all population classes.

As in previous models, there is an RMS capacity constraint. In order to ensure an equitable allocation, we require the percentage savings of population classes to differ by no more than a given threshold. Although we still measure equity in monetary terms, this is just one example of how social considerations can be incorporated. Another method for incorporating equity, for example, would be to introduce a constraint that forces equitable quality of life benefits.

Define $\mathcal{I}^{RMS} \subseteq \mathcal{I}$ as the set of population classes which could benefit from RMS:

$$\mathcal{I}^{RMS} = \left\{ i \in \mathcal{I} : C_i^1 < C_i^0 \right\}. \tag{8}$$

Assuming there are population classes that cannot be treated with a traditional bundle, but can benefit from RMS, future research could examine a model variant that considers equity when maximizing the number of patients that can be treated.

Data elements

α: maximum difference in percent savings allowed between population classes

Decision variables

A_i: total annual expected cost per patient for patients in population class i
v: the smallest percentage savings any population class receives
w: the largest percentage savings any population class receives

Objective function

$$minimize \sum_{i\in\mathcal{I}} n_i A_i \tag{9}$$

Constraints

$$\sum_{b\in\mathcal{B}_i} y_i^b = 1 \quad \forall\, i \in \mathcal{I}, \tag{10}$$

$$A_i = \sum_{b\in\mathcal{B}_i} C_i^b y_i^b \quad \forall\, i \in \mathcal{I}, \tag{11}$$

$$\sum_{i \in \mathcal{I}} \sum_{b \in \mathcal{B}_i} n_i u_k^b y_i^b \leq r_k \quad \forall\, k, \tag{12}$$

$$v \leq \frac{C_i^0 - A_i}{C_i^0} \quad \forall\, i \in \mathcal{I}^{RMS}, \tag{13}$$

$$w \geq \frac{C_i^0 - A_i}{C_i^0} \quad \forall\, i \in \mathcal{I}^{RMS}, \tag{14}$$

$$w - v \leq \alpha, \tag{15}$$

$$0 \leq y_i^b \leq 1 \quad \forall\, i \in \mathcal{I},\ b \in \mathcal{B}_i. \tag{16}$$

Constraints (10) are repeated from the previous model. Constraints (11) calculate the total cost per patient for population class i. Constraints (12) ensure the availability limits are respected. Constraints (13) and (14) compute the smallest and largest percentage savings over all classes that can benefit from RMS. Finally, Constraint (15) ensures that the difference between the largest percentage savings and smallest percentage savings is less than a given bound.

4. Case Study

To illustrate and demonstrate the value and insight the models discussed in the previous section may provide, we have conducted a computational study. It is simplified in the sense that we focus on a small subset of chronic illnesses: diabetes, heart failure, and hypertension. These particular chronic illnesses are chosen because they affect over one third of the U.S. adult population, and improved disease management via RMS has been shown to decrease the occurrence of complications (Darkins *et al.*, 2008). We focus on demonstrating the usefulness of the model for policy makers in determining allocation and reimbursement schemes. Therefore, we exclude indirect costs associated with loss of productivity due to screenings and complications. Typically, these indirect costs to patients are not reimbursed by healthcare payers. Excluding indirect costs from the case study results in underestimating the total savings potential associated with RMS, because indirect costs are lower when RMS is used due to less time spent visiting doctor's offices, for example.

Care has to be taken when interpreting the results of our computational experiments as we faced a number of challenges in terms of populating the models with realistic and reliable data. The model is most useful as a decision analysis tool when good data is available. Data challenges are a common phenomenon in economic and decision models for healthcare problems. To account for some of the uncertainty in the data, specifically the reduction in risk for complications associated with using RMS, we have decided to conduct sets of experiments in which we use "optimistic" (high) and "moderate" values for risk reduction parameters associated with monitoring system use. The values are taken from clinical literature that documented varying levels of success achieved via RMS use.

Table 2. Persons per population class

i	n_i	Reference	Explanation
PD	22,200,000	Benjamin *et al.,* 2003	8.32% of 2005 US population has been diagnosed prediabetic
T1D	1,300,000	CDC, 2005; Harris *et al.,* 1998	6.48% of 2005 US population is diabetic; 7.5% are Type I
T2D	16,000,000	CDC, 2005; Harris *et al.,* 1998	6.48% of 2005 US population is diabetic; 92.5% are Type II
HF	5,000,000	Lehmann, 2005	2005 estimate
HYP	50,000,000	Ostchega *et al.,* 2008	Only includes those *aware* of condition in 2005

4.1. *Population classes and monitoring bundles*

Five population classes are included in the computational study: prediabetes (PD), Type I diabetes (T1D), Type II diabetes (T2D), heart failure (HF), and hypertension (HYP). The separate classes corresponding to diabetes are introduced because risk for complications and recommended treatment guidelines vary based stage of disease. We assume that patients can only belong to one class, i.e., we do not consider patients with multiple diseases. The number of persons in each population class are reported in Table 2, along with the source of information and an explanation of how the number is determined. The risk for complications and cost of treatment specific to each population class and bundle are discussed in Sections 4.2 and 4.3.

4.2. *Complication risks and costs*

Associated with each population class in the case study is a set of complications for which persons with the disease are at increased risk. The data required by models presented in this paper include the cost of each complication and the risk that persons in a population class using a specific treatment bundle experience the complication. For some population classes, the necessary data could not be obtained for a subset of complications for which the population class is at risk. Those complications are excluded from the study. As

Table 3. Cost of complications

Complication	Cost (\$/yr)	Population classes at increased risk
Kidney failure	9920	PD, T1D, T2D, HYP
Retinopathy	4720	PD, T1D, T2D
Heart disease	12300	PD, T1D, T2D, HYP
Stroke	12300	PD, T1D, T2D, HYP
Heart attack	25000	HYP
Healthcare utilization	9623	HF

the expected cost of each complication is never higher in the RMS bundle than in the traditional system, excluding some complications from consideration has the effect of underestimating the savings potential of RMS.

Table 3 lists the set of complications considered in this case study, along with their estimated costs. The estimated costs of kidney failure and blindness due to retinopathy are taken directly from Caro *et al.* (2002), which additionally estimates the cost of macrovascular disease (heart disease and stroke) as $24,600. We assume the cost of macrovascular disease can be split equally among heart disease and stroke. The average cost per year of a heart attack was taken from Weisser and Gengler (2006). The expected annual condition-specific healthcare utilization costs for HF patients have been estimated as $9,623 (Center for Healthcare Research and Transformation, 2010). This is the result of frequent trips to the doctor, hospital, and emergency room that occur when acute symptoms associated with HF occur.

The risk for complications experienced by members of a population class using a specific treatment bundle is given in Table 4. While the clinical literature consistently reports decreased risk for complications when RMS is used, the magnitude of improvement reported varies. Thus, we consult the literature to derive "moderate" and "optimistic" (high risk reduction) scenarios. The second column in the table denotes the bundle (b) and risk reduction (r) scenario (*mod* or *opt*). Unreported risk values indicate the population class is not at increased risk for the complication. A detailed discussion of the determination of values reported in Table 4, along with appropriate references, is included in Appendix A.

4.3. *Treatment bundle descriptions and costs*

As previously stated, two treatment bundles are considered for each population class included in the study; $b = 0$ corresponding to the traditional delivery environment where care is provided during physician office visits, and $b = 1$ corresponding to the RMS. Describing differences in procedure frequencies and cost structure between the two bundles here will clarify the discussion that follows:

- Each procedure in each bundle has a direct cost. For medical tests, this is comprised of the test supply costs (e.g., test strips). Some medical tests have no direct cost because disposable supplies are not required (e.g., blood pressure). For office visits, the direct cost is estimated as $160, the average cost of a physician office visit (AHRQ, 2007). Procedures such as patient education and reminders have no direct cost because the cost is assumed to be built into the direct cost of the office visit during which they are delivered, or the cost of the RMS, which uses scripted electronic content to deliver education and reminders.
- In $b = 0$, recommended procedures are performed during doctor's office visits, with noted exceptions (e.g., blood glucose is tested at home). Procedures are only performed as frequently as a specific medical test or physician office visit is recommended.
- In $b = 1$, recommended procedures are performed at home. Procedures with no direct cost (certain medical tests, patient education, patient reminders) are performed daily. Procedures with direct costs are performed according to the same frequency as in $b = 0$.

The direct cost of each procedure and the relevant frequencies for each population class and treatment bundle are summarized in Table 5. The monitoring procedures we consider include fasting plasma glucose (FPG), hemoglobin (A1C), capillary blood glucose (CBG), blood pressure (BP), weight, urinalysis, electrocardiogram (ECG), and cholesterol tests. A detailed discussion of the determination of the values reported, along with appropriate references, is included in Appendix B.

4.4. *Pricing model for RMS*

Through conversations with multiple home care agencies, we estimate the purchase price of the RMS to be $600, regardless of the peripherals which are included. There is a transmission cost per device of $180/yr, associated with maintaining an internet or broadband connection to communicate health readings to a remote server. In addition to the purchase price and transmission cost, there is a monitoring cost. Home care executives estimate that one nurse, whose sole responsibilities include monitoring and following up with patients based on incoming health data, can manage 100 patients on RMS annually. Thus, using the average nurse salary reported by the Bureau of Labor Statistics, $60,000 (2010–2011), divided across 100 patients, we assume a monitoring cost of $600 per year per system. Much research in automatic detection of anomalies (deviations from expectations in health indicators) is being carried out. With the help of such techniques, each nurse may be able to monitor a larger number of patients in the future.

4.5. *Capacity constraints and equitability concerns*

RMS capacity can be limited by the number of nurse-hours available for monitoring incoming transmissions and following up with patients, or by the number of devices available for distributing to patients. In our experiments we assume nurse-hours are the limiting factor, due to the current nursing shortage and rapid expansion of the home health technologies market. As described in Section 4.4, one patient is expected to require 0.01 nurse work years in monitoring efforts. Letting $k = 1$ represent the nurse

Table 4. Risk for complications (%) by population class, bundle, and risk reduction scenario

i	(*b*,*r*)	Kidney failure	Retinopathy	Heart disease	Stroke	Heart attack	Util.
PD	(0,-)	2.5	1.44	0.39	0.39		
PD	(1,*mod*)	0.81	0.04	0.11	0.11		
PD	(1,*opt*)	0.63	0.036	0.036	0.08		
T1D	(0,-)	30	2.3	6.23	6.23		
T1D	(1,*mod*)	20	1.5	4.2	4.2		
T1D	(1,*opt*)	18	1.38	3.115	3.115		
T2D	(0,-)	40	0.023	0.0623	0.0623		
T2D	(1,*mod*)	30.8	1. 5	4.2	4.2		
T2D	(1,*opt*)	24	1.38	3.115	3.115		
HF	(0,-)						100
HF	(1,*mod*)						80
HF	(1,*opt*)						70
HYP	(0,-)	3.81		4.31	5.64	1.6	
HYP	(1,*mod*)	2.63		2.97	3.89	1.1	
HYP	(1,*opt*)	1.68		1.90	2.48	0.7	

resource, u_1^1, the amount of nurse resource required by one patient using RMS annually, is equal to 0.01.

According to the United States Bureau of Labor and Statistics, there were 2.6 million registered nurses employed in 2008 (Bureau of Labor Statistics, 2010–2011), following the distribution of employment by health sector given in Table 6.

Primary care physicians and home health agencies are typically responsible for providing daily care management for chronic disease patients. Thus, we assume those two sectors, representing 13% of total RN employment, will be providing most of the remote health monitoring capability. In our experiments, we assume these sectors will be willing to dedicate 10% of their nursing resources to monitoring systems in a low-capacity scenario (38,000 of the 380,000 nurses available). We also test a high-capacity scenario, which assumes the healthcare delivery system undergoes a more radical transformation, and primary care and home health sectors are willing to dedicate 25% of their nursing resources to RMS (84,500 nurses). These scenarios are represented by Equations (17) and (18), respectively:

$$\sum_{i \in \mathcal{I}} 0.01 n_i y_i^1 \leq 38{,}000, \tag{17}$$

$$\sum_{i \in \mathcal{I}} 0.01 n_i y_i^1 \leq 84{,}500. \tag{18}$$

We model equitability as limiting the difference in total potential savings per patient between any pair of population classes that can benefit from RMS to be less than α. We experiment with $\alpha = 0.05, 0.10$.

5. Experiments

We present the results of our experiments using the uncapacitated, capacitated, and capacitated with equitability models below.

Table 5. Procedure cost and frequency data for each population class and treatment bundle

		Annual frequency, $b = 0$					Annual frequency, $b = 1$				
Procedure	Cost ($)	T1D	T2D	PD	HF	HYP	T1D	T2D	PD	HF	HYP
FPG	0.40	4	4				4	4			
A1C	29.9	4	4				4	4			
CBG	0.40	730	1460	1			730	1460	1		
BP	0	4	4	1	4	104	365	365	365	365	104
Weight	0			1	4			365	365		
ECG	0					1					1
Cholesterol	14					1					1
Urinalysis	0.30					1					1
Office visit	160	4	4	1	4	1					
Patient ed.	—	4	4	1	4	1	365	365	365	365	365
Reminders	—						365	365	365	365	365

5.1. *Uncapacitated model*

Table 7 presents the expected cost per patient per year for each population class if bundle 0 or 1 is used. The table then also presents the assignment of population classes to bundles indicated by the uncapacitated model solution. In both the moderate and optimistic risk reduction scenarios, RMS is the most cost-effective treatment bundle for population classes T1D, T2D, and HF. The traditional bundle is more cost-effective for population classes PD and HYP. Thus, all members of T1D, T2D, and HF receive RMS, while PD and HYP continue to use the traditional bundle. Because PD and HYP do not experience expected cost savings as a result of RMS use, the percent savings associated with broad RMS introduction we report for the remainder of this paper excludes classes PD and HYP. Table 8 reports the total expected annual cost if all members of T1D, T2D, and HF continue to use the traditional bundle, and then the percent savings that can be realized if the solution specified by the uncapacitated model is implemented. In the moderate risk reduction scenario, the total savings potential associated with broad RMS introduction is 6.26%. In the optimistic risk reduction scenario, the total savings potential increases to 13.3%. These solutions require the availability of 22.3 million systems and 223,000 nurses.

5.2. *Capacitated model*

Table 9 presents results of the capacitated model, in which there is limited nurse capacity to monitor and follow up with the patients using RMS. In the low capacity scenario (LC), capacity is limited to 10% of the home health and primary care nurse workforce, such that 38,000 nurses can monitor 3.8 million systems annually. In the high capacity scenario (HC), capacity is limited to 25% of the workforce, such that 8.45 million systems can be monitored annually.

The optimal solution to both the moderate and optimistic risk reduction scenarios when capacity is low is to allocate all RMS capacity to the HF population class. This is an intuitive result, as HF realizes higher potential savings from RMS than do T1D and T2D. There are 5 million people in the HF population class, and 3.8 million of them (76% of the class) receive the systems available. As reported in Table 10, the associated savings across T1D, T2D, and HF are 1.54% and 2.8% in the moderate and optimistic risk reduction scenarios.

In the high capacity scenario, all members of HF receive systems (5 million patients). The remaining systems are allocated to 3.45 million members of T2D (21.6% of the class). No systems remain to be allocated to T1D, the population class that realizes the lowest potential savings from RMS use. The total savings associated with the moderate and optimistic risk reduction scenarios are 3.22% and 6.2% (Table 10).

Note that the following greedy algorithm could be used to determine the optimal assignment of the current model:

Table 6. Percentage of RNs employed, by health sector

Sector	% of total RNs
Hospitals	60
Physician offices	8
Home health	5
Nursing homes	5
Employment services	3
Other	19

Table 7. Uncapacitated model solution

Population class	Expected cost/pt/yr			Fraction assigned to b	
	$b = 0$	$b = 1, mod$	$b = 1, opt$	$b = 0$	$b = 1$
PD	572.30	1489.70	1464.28	1	0
T1D	5666.50	4881.40	4410.43	0	1
T2D	6950.50	6244.76	5297.63	0	1
HF	10263.00	9078.40	8116.1	0	1
HYP	2176.10	2773.98	2274.7	1	0

Table 8. Total expected costs and savings associated with uncapacitated model solutions

Solution description	Risk	Total cost	Percent savings
All members of T1D, T2D, HF use $b = 0$	NA	\$291,399,510,000	—
All members of T1D, T2D, HF use $b = 1$	*mod*	\$273,164,040,000	6.26%
All members of T1D, T2D, HF use $b = 1$	*opt*	\$252,586,199,000	13.3%

Table 9. Capacitated model solution

Population class	# pts (millions)	Fraction assigned to $b = 1$	
		LC	HC
T1D	1.3	0	0
T2D	16	0	21.6
HF	5	0.76	1

Table 10. Total expected costs and savings associated with capacitated model solutions

Risk	Capacity	Total cost	Percent savings
mod	LC	\$286,898,030,000	1.54%
opt	LC	\$283,241,290,000	2.8%
mod	HC	\$282,016,842,600	3.22%
opt	HC	\$273,319,800,300	6.2%

Table 11. Capacitated model with equitability solutions

α	Cap	Risk	Fraction receiving devices			Population class % savings			Total % savings sav
			T1D	T2D	HF	T1D	T2D	HF	
0.05	LC	*mod*	0.056	0.077	0.50	0.78%	0.78%	5.77%	1.33%
0.05	LC	*opt*	0.121	0.113	0.367	2.68%	2.68%	7.68%	2.45%
0.05	HC	*mod*	0.216	0.294	0.692	2.99%	2.99%	7.99%	2.62%
0.05	HC	*opt*	0.337	0.314	0.596	7.48%	7.48%	12.48%	5.23%
0.10	LC	*mod*	0	0	0.76	0	0	8.77%	1.54%
0.10	LC	*opt*	0.066	0.061	0.547	1.45%	1.45%	11.45%	2.61%
0.10	HC	*mod*	0.784	0.152	1	10.87%	1.54%	11.54 %	2.90%
0.10	HC	*opt*	0.282	0.263	0.777	6.24%	6.24%	16.24%	5.40%

(1) rank population classes in non-increasing order of potential savings from RMS, (2) remove population class from top of list and allocate systems to as many members of the population class as possible, (3) if capacity remains, select the next population class from the list and repeat from (2), otherwise, stop.

5.3. *Capacitated model with equitability*

In previously considered models, population classes with the largest potential savings associated with RMS use received priority allocation of systems. This resulted in certain population classes not receiving systems at all. When equitability is considered, savings are distributed more evenly across the population classes. Table 11 presents results of the capacitated model with equitability, where the differences in percent savings between pairs of population classes that can benefit from RMS are limited to $\alpha = 5\%$ and 10%.

As capacity increases, the fraction of each population class receiving systems increases, as there are more systems available for allocation. As α, the equitability parameter increases, the fraction of HF receiving systems always increases, most often at the expense of decreases in the fractions of T1D and T2D receiving systems. This result is intuitive. As the level of inequity is allowed to increase, the expected cost minimization model is biased towards allocating more systems to HF, the population class that derives the most financial benefit. As the risk reduction factor increases from moderate to optimistic, the fraction of HF receiving systems *decreases*. This occurs because as risk reduction increases, RMS essentially becomes more effective at preventing costly complications. Higher relative savings are experienced by members of HF than T1D and T2D, thus the RMS allocation to HF must decrease in order to avoid violating equitability conditions with respect to T1D and T2D.

The maximum number of systems allocated to HF among all scenarios is 5 million, when capacity is high, $\alpha = 0.10$, and risk reduction is moderate. The maximum number of systems allocated to T1D occurs in the same scenario, with 1.019 million members of T1D receiving systems. The maximum number of systems allocated to T2D is 5.024 million, when capacity is high, $\alpha = 0.05$, and risk reduction is optimistic.

6. Conclusions and future research

According to the data collected from the clinical literature and used in our computational study, HF, T1D, and T2D population classes could realize cost savings if RMS are broadly introduced to enhance care delivery. When population classes are ranked in non-increasing order of expected cost savings from using RMS, the resulting list is HF, T2D, T1D. Thus, if maximizing potential savings is the primary objective and RMS capacity is limited, systems should be allocated to population classes in the specified order. When social and quality of life considerations are incorporated in the decision making process, an equitable allocation for RMS assigns more systems to T1D and T2D, and fewer to HF.

It should be noted that cost savings correspond with expected improvements in care outcomes, as frequency of complications is expected to decrease. For HYP and PD, complication frequency is expected to decrease if RMS are used, but the expected benefits do not outweigh the associated direct costs, given the conservative estimates used in our computational study. The expected annual cost of the RMS bundle would need to decrease by approximately \$900 in order for PD to realize cost savings, and by \$100 for HYP. While these simple estimates were derived from information contained in Table 7, the model could be used to perform this kind of dual analysis as well. Note that we currently assume the purchase price of RMS to be \$600, but as mentioned earlier, devices that communicate with mobile apps are in development. If these new devices and apps have negligible purchase cost, then the expected savings for HYP would justify the annual transmission and monitoring expenses.

The following assumptions of our computational study result in conservative savings estimates for the broad introduction of RMS. First, certain complications, for which reliable data was not available at the time the study was performed, were excluded from consideration. Because complication risk decreases with RMS use, expected benefits (and savings) would increase if additional complications were considered. Second, our analysis assumes a one-year model where the full purchase price of the RMS is allocated in its first year of use. Under common accounting principles, the RMS may be considered a depreciable asset, and therefore, only a portion of its cost would be allocated to one year. Third, because we take the perspective of a provider or payer and focus only on what would be considered real costs, indirect costs associated with loss of productivity and improved potential quality adjusted life years are not included in the computational study. Relaxing these assumptions would increase the estimated savings for each of the population classes.

While clinical studies have shown that monitoring systems improve patient care outcomes, there is some uncertainty in the magnitude of reduction in risk for complications that is realized. Thus, we experimented with moderate and optimistic scenarios for risk reduction. When optimistic risk reduction is achieved, the total savings potential of the uncapacitated introduction of RMS is 13.3%; equivalent to almost 40 billion dollars in annual savings. These expected savings decrease to 6.2% and 2.8% when less restrictive and more restrictive capacity limits are placed on monitoring systems, respectively. If a moderate level of risk reduction is assumed, the uncapacitated savings decrease to 6.6%, and the capacitated savings decrease to 3.2% and 1.33%. Even in the most conservative scenario, 1.33% cost savings translates to almost 3.9 billion dollars annually.

In the current health insurance environment, major payers such as Medicare do not reimburse for monitoring system usage. Specifically, in the home care environment, home health agencies wishing to enhance the care they deliver with monitoring systems must bear the costs for those systems themselves. The systems can be especially useful in the home health environment, by allowing videoconference nurse visits, and enabling the home care agency to be informed about a patient's health in between home-visits. While some federal grants have recently been administered to encourage monitoring system adoption, we believe this study provides convincing evidence that adoption should be more widespread, and reimbursement schemes should be reconsidered. For certain population classes, payers can decrease their total enrollee expenditures by increasing what is spent on monitoring systems. It is also worth noting the impact of healthcare reform on this approach. In the Patient Protection and Affordable Care Act of 2010, there is much emphasis on comparative effectiveness. The legislation also specifies that reimbursement will be reduced for hospitals with high rates of preventable readmissions for common conditions such as HF. There is a huge incentive on the part of providers to make use of home health care and home monitoring to prevent readmissions.

An area for future research is to extend the study for additional diseases that could benefit from monitoring system usage. The data gathered for this paper required extensive search of the clinical literature, thus a limited number of the most common chronic diseases were included in the case study. Additionally, model extensions discussed throughout the paper could be examined.

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Appendix A. Explanation of values in Table 4

T1D and T2D

Under the traditional delivery system bundle ($b = 0$), the risk of developing kidney failure is 30% for T1D and 40% for T2D (National Kidney Foundation, 2014). The risk of retinopathy and stroke is 2.3% and 6.23% for both population classes, respectively (Hoerger *et al.*, 2004). Data regarding risk for heart disease could not be attained, but we assume here it is equal to the risk for stroke, both being macrovascular diseases.

Under the RMS bundle, these risks are reduced. A survey of 21 studies of telehealth, a form of RMS, showed a positive impact on glycemic control (reduced A1C levels) (Polisena *et al.*, 2009). Clinical research has demonstrated that a one percent reduction in A1C levels corresponds to a 40% reduction in the risk for kidney failure and retinopathy (CDC, 2005b). Controlling blood pressure has been shown to achieve 33% reduction in risk for these two complications, and 33% to 50% reduction in risk for heart disease and stroke (CDC, 2005b). Thus, in the moderate risk reduction scenario (1,*mod*) for T1D and T2D, complication risks are reduced from their $b = 0$ levels by 33%. In the optimistic risk reduction scenario (1,*opt*), kidney failure and retinopathy risks are reduced by 40% and heart disease and stroke risks by 50%.

PD

Prediabetic patients are at risk of progressing to Type II diabetes, and then subsequently at risk for the same complications as T2D. Evidence has shown the rate of progression to be 25% over three to five years (Nathan *et al.*, 2007). We assume the rate is linear, and divide the risk across four years to obtain an annual risk of progressing to Type II diabetes of 6.25%. Then, the risk for a complication for a person in the PD population class using $b = 0$ is estimated as (*risk of progressing to T2D*)∗(*risk person in T2D using* $b = 0$ *has for complication*). For example, the risk for kidney failure is $6.25\% * 40\% = 2.5\%$.

Clinical research has shown that lifestyle interventions can reduce the risk of progression from PD to T2D by 58% (CDC, 2008). Because RMS enables very aggressive lifestyle interventions, we assume this reduction in risk of progression (from 6.25% to 2.625%) is achieved by RMS. Then, the risk for a complication for a person in the PD population class using $b = 1$ and risk reduction scenario r is estimated as (*risk of progressing to T2D using* $b = 1$)∗(*risk person in T2D using* $b = 1$ *in risk reduction scenario* r *has for complication*). For example, the risk for kidney failure in (1,*mod*) is $2.625\% * 30.8\% = 0.8\%$. In (1,*opt*), the associated risk is $2.625\% * 24\% = 0.63\%$.

HF

The expected annual condition-specific healthcare utilization costs for HF patients have been estimated as $9,623 (Center for Healthcare Research and Transformation, 2010). A Veteran's Health Administration (VHA) study indicated these annual costs were decreased by 26% in a telehealth program (Darkins *et al.*, 2008). Because healthcare utilization costs are reported as an expected annual cost for HF patients, instead of being reported as the cost of specific episodes of acute care and the expected frequency of such episodes, we model the risk and cost of complications for HF patients as follows. In $b = 0$, we assume HF patients are at 100% risk for incurring $9,623 in annual condition-specific acute care utilization charges. Using the findings of the VHA, we associate a 20% reduction in expected costs with the moderate risk reduction scenario, and a 30% reduction with the optimistic scenario. Thus, there is 80% risk in (1,*mod*) and 70% risk in (1,*opt*) of incurring $9,623 in annual healthcare utilization charges.

HYP

For hypertensive patients using $b = 0$, the risk in one year of having a heart attack or stroke is 1.6% and 5.64% respectively (Davis, 2009; Wolf *et al.*, 1991; American Heart Association, 2013a,b). The risk of developing heart disease or kidney failure is 4.31% and 3.81% respectively (Spader, 2011; Life Options, 2011; American Heart Association, 2013a,b). Studies have shown that the risks of these complications can be reduced when a patient lowers their blood pressure and follows healthy lifestyle recommendations. Based on Green *et al.* (2008), we assume moderate and optimistic risk reduction values, for each of these complications, of 31% and 56%.

Appendix B. Explanation of values in Table 5

T1D and T2D

The risk for complications experienced by patients in population classes T1D and T2D can be reduced by controlling blood glucose, blood pressure, blood lipids, following a healthy diet and obtaining regular exercise, and receiving preventive care in a timely manner (CDC, 2008). Thus, the monitoring procedures we consider for T1D and T2D include fasting plasma glucose (FPG), hemoglobin (A1C), capillary blood glucose (CBG), and blood pressure (BP). Patient education, follow-up, and reminders are recommended to achieve lifestyle compliance and enable timely interventions.

In $b = 0$, quarterly consultations with caregivers are recommended. We assume that FPG, A1C, BP, and patient education occur during the quarterly consultation (physician office visit). The CBG test should be performed daily for T2D patients, and four times per day for T1D patients. This test is performed at home using a simple testing device. According to the website Test Medical Symptoms at Home, the direct supply cost associated with FPG, A1C, and CBG are $0.40, $29.95, and $0.40, respectively (Test

Medical Symptoms at Home, Inc., 2010). In $b = 1$, all tests are performed at home using the RMS. FPG, A1C, and CBG are performed at the same frequency as in $b = 0$, but BP is performed daily because it has no associated direct supply cost. Patient education and reminders occur daily.

PD

Patients in the PD population are at risk for developing T2D, but this can be delayed if people lose weight and increase their physical activity to return blood glucose levels to normal. Thus, the monitoring procedures we consider for PD include weight, BP, CBG, and patient education and reminders. In $b = 0$, weight, BP, and CBG are tested once per year during an annual recommended physician office visit. Patient education also occurs during this visit. In $b = 1$, weight and BP are monitored daily, patient education and reminders occur daily, and CBG is tested once per year.

HF

The AHA recommended treatment for HF includes close observation and follow-up to ensure patient adherence to a healthy lifestyle and medication compliance (Jessup *et al.* 2009). Additionally, blood pressure and weight should be monitored on a regular basis, and quarterly consultations with caregivers are recommended. In $b = 0$, weight and BP are tested during quarterly visits, during which patient education regarding lifestyle and medication compliance occurs as well. In $b = 1$, weight and BP are monitored daily and close observation and follow-up are achieved through daily patient education and reminders.

HYP

Lowering blood pressure can reduce a hypertensive patient's risk for heart attack, stroke, kidney disease, and heart failure. The American Heart Association recommends following a healthy diet, regularly exercising, maintaining a healthy weight, managing stress, avoiding tobacco, limiting alcohol, and complying with medication prescriptions to lower and control blood pressure (2013a,b,c). Therefore, the monitoring procedures we consider for HYP are BP, urinalysis, electrocardiogram (ECG), and cholesterol tests (Mayo Clinic, 2012). Hypertensive patients are recommended to measure and record their blood pressure twice each week at home and every year with their physician. Urinalysis, ECG, and cholesterol tests are performed yearly at their follow-up procedure to check for complications that develop due to high blood pressure (WebMD, 2011).

Thus, $b = 0$ includes yearly ECG, cholesterol tests, and urinalysis during an annual physician office visit. BP is tested twice daily at home. The direct cost of testing supplies for a cholesterol test is $14. The additional cost of a single urinalysis test is $0.30 (WebMD, 2011). In $b = 1$, the ECG, cholesterol test, and urinalysis, and BP measurement are performed at home with the same frequencies as $b = 0$. However, patient education and reminders are performed on the device daily.