The Promise and Value of Remote Monitoring Devices

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Abstract

Caring for patients with chronic illnesses is costly - over a trillion dollars in 2006. These costs are likely to rise significantly in the future as the number of people with chronic illnesses is expected to increase dramatically. New technologies, most prominently remote monitoring devices, are likely to change the care environment for patients with chronic illnesses and will alleviate some of the anticipated resource shortages and potentially reduce the number of occurrences of serious, costly complications. These technological advances may provide a more cost-effective and less labor-intensive way to manage the care of patients with chronic illnesses. We study the potential societal value of such remote monitoring devices by developing a model that estimates the value of providing remote monitoring devices to target populations. 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 devices.
1 Introduction

Caring for patients with chronic illnesses is costly - over a trillion dollars in 2006. These costs are likely to rise significantly in the future, as the number of people with chronic illnesses is expected to increase dramatically. This expected increase is mainly due to an aging population, since the risk for chronic diseases increases with age. By 2040, one out of every five Americans will be over 65 and the number of people aged 85 and older will have tripled or quadrupled. However, it is not only an aging population that causes a rise in chronic illnesses. An additional 2.6 million people were diagnosed with diabetes since 2002, for example. This is an increase of more than 10%, and cannot be attributed solely to an aging population but also to factors such as changing demographics (Hispanics are more likely to have diabetes than other race/ethnic groups) and an increase of obesity.

The costs associated with chronic illnesses can be divided into three primary categories. First, there are the direct costs associated with monitoring the disease on an on-going basis, which involves among other things regular visits to and consultations with care givers. Second, there are the indirect costs associated with the loss of productivity due to regular monitoring/screening visits at clinics or hospitals. Finally, there are the costs associated with any complications that may arise and may require emergency room visits and/or surgery. There is also the impact that the illness has on the quality of life, though these costs are often difficult to quantify.

New technologies, most prominently remote monitoring devices, are likely to change the care environment for patients with chronic illnesses and will alleviate some of the anticipated resource shortages and potentially reduce the number of occurrences of serious, costly complications. Remote monitoring involves collecting disease-specific metrics from biomedical devices used by patients in their homes or other settings outside a clinical facility. Remote monitoring systems typically collect patient readings and then transmit them to a remote server for storage and later examination by health care professionals. Once available on the server, the readings can be used in numerous ways by home health agencies, by physicians, and by informal care providers.

Intel recently announced a consortium of 22 health care and technology companies that will set technology standards for home health care monitoring devices. The aim is to provide better preventive medical care and reduce unnecessary visits to the doctor and to
the emergency room. The group plans to develop devices to serve several segments of the population: (i) the one billion adults worldwide who are considered to be obese, (ii) the 860 million people with a chronic disease, and (iii) the growing elderly population. The goal is to feed data from weight scales, blood pressure monitoring devices, and, for the elderly, sensors in the home, to a network that will allow health care providers and family members to monitor a person’s condition.

As these remote monitoring devices are installed in the patients’ homes and operated by the patient themselves, their use will free up space and time in the clinics and hospitals that these patients currently visit regularly to have the status and progression of their disease monitored, or, in case the patients are unable to visit a clinic or a hospital, the time of the care givers that visit these patients at their home. Furthermore, by providing care givers timely, and maybe more frequent, access to a patient’s health status, these care givers can provide patients appropriate preventive interventions, helping to avoid hospitalization and improve patients’ quality of care and quality of life. As such, remote health care has the promise of reducing health care costs by focusing on preventive measures and monitoring instead of emergency care and hospital admissions.

These technological advances may provide a more cost-effective and less labor-intensive way to manage the care of patients with chronic illnesses. It is the goal of this paper to analyze the societal value of such remote monitoring devices. The potential benefits of remote monitoring devices will be discussed in more detail along with an approach for quantifying those benefits where possible. A model is developed that estimates the value of providing remote monitoring devices to target populations. 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 devices.

To illustrate and demonstrate the value and insight the model may provide, we have conducted a small, simplified computational study. It is simplified in the sense that we focus on a very small subset of chronic illnesses: diabetes and heart disease. The computational study shows that, under reasonable assumptions, the broad introduction of remote monitoring devices will lead to substantial societal benefits as estimated cost savings for the target populations will be in the order of 205 billion dollars annually, or a little over 7%. We should mention that we assume that the population follows recommended guidelines for screening, testing, and treatment. Our estimate, therefore are estimates for the potential
value since not all patients follow recommended guidelines.

The remainder of the paper is organized as follows. In Section 2, we discuss remote monitoring devices. In Section 3, we focus on the value of monitoring devices in the home care industry. In Section 4, we introduce the models we propose for assessing the societal benefits of remote monitoring devices. In Section 5, we present the results of the computational study. Finally, in Section 6, we elaborate on future research and model extensions.

2 Remote Monitoring Devices

Several companies already offer in-home monitoring devices and the market for as well as the capabilities of these devices is expected to grow exponentially. For our purposes, it is convenient to consider a generic in-home monitoring device that has the ability to take blood pressure readings, perform on-chip blood tests, and carry out a variety of other medical tests. We will assume that the device consists of a base unit able to perform a number of functions and peripherals that can be attached to the base unit to provide additional functionality. Apart from performing medical tests, the in-home monitoring device also has the ability to transmit results to a receiving station, using an internet connection, wi-fi, or satellite link.

There is a plentitude of benefits associated with the use of these in-home monitoring devices. They can save travel time and costs for patients; visits to a medical clinic or a hospital may no longer be required. They free up much needed capacity at clinics and hospitals by moving the demand for relatively simple monitoring services out of these facilities. For those patients that were unable to visit a medical clinic or a hospital, but had to rely on the visits of a care giver to their home for monitoring services, it frees up the time of the care giver responsible for such visits. Given the looming registered nursing shortage, in-home monitoring devices may provide much needed relief. They can assist with the simple but important task of reminding patients to take their medicine. Maybe most importantly, their use may result in early detection of medical conditions thereby preventing costly emergency visits and hospitalizations. The collection of large amounts of (real-time) data will also open up immense data mining opportunities, which in turn may lead to improved quality of treatment and fewer serious illnesses or complications.
3 Monitoring devices in home care industry

Home care provides professional health care services to patients who are well enough to stay at home but cannot care for themselves or be completely cared for by friends and family. The National Association for Home Care and Hospice (NAHC) estimates that there are approximately 20,000 providers nationwide and 7.6 million receivers of home care with annual expenditures estimated at $38.3 billion in 2003 (NAHC 2004). According to the Visiting Nurses Association of America, people who are chronically or terminally ill are among the groups most often using home care services (VNAA 2007). Thus, demand for long-term care is increasing, but the supply of care givers is decreasing. Because of this, maximum utilization of the given nursing resources is a top priority. Providing home care nurses with home monitoring devices could increase their productivity in the following manner.

During each workday, a home care nurse is given a list of scheduled visits to patients’ homes that must be performed during the day. A potential source of lost productivity for home care nurses is the completion of required lab work. One home health agency has estimated that one-fourth of their patient visits require a lab to be processed. In some cases, the closest allowable lab processing facility is fifteen miles away from the current patient. This results in lost productivity for the nurse, who must spend time driving to a lab processing facility when they would otherwise be performing additional patient visits.

The use of home monitoring devices could alleviate this situation. If each home care nurse carries a monitoring device to all their scheduled in-home visits, the peripherals on the device could be used to process the labs in the patients’ homes.

There could be implementation challenges associated with providing a monitoring device for each home care nurse, but it is likely that these challenges will be restricted to training the nurses to use the testing peripherals. Many home care nurses are currently provided with a laptop computer they take to each patient’s home to document patient visits. Because the home monitoring devices would also be equipped with this functionality, their current laptops could be completely replaced by the new home monitoring devices.
4 Assessing the Societal Benefits of Monitoring Devices

To introduce a model aimed at assessing the societal benefits of home monitoring devices, a few concepts are introduced. A population class represents a group of patients with the same “disease.” Because patients at different stages of a disease typically require different treatment, e.g., a person with late-stage heart disease requires more monitoring and different medication than a person with early-stage heart disease, a separate population class is introduced for each stage of a disease. Each disease, and thus each population class, has a set of complications that may or may not occur at some point during the progression of the disease. For example, a patient with Type II Diabetes may develop retinopathy. One reason for carefully monitoring people with chronic illnesses is preventing costly complications. A monitoring bundle for a population class is a set of monitoring procedures that patients belonging to the class undergo regularly. Each monitoring procedure in the bundle has an associated frequency, which indicates how often the procedure is performed in a given period, a direct cost, representing the cost of performing the procedure, and an indirect cost, capturing the loss of productivity when the procedure is performed. We associate with each monitoring bundle a probability of occurrence for each of the complications that may occur for the disease. These probabilities, of course, depend on the frequency with which monitoring procedures are performed. Therefore, a monitoring bundle captures more than just the types of monitoring procedures that are performed for a population class. Similarly, a monitoring bundle allows us to capture different ways in which a monitoring procedure can be performed. One possibility may be to visit a clinic where the monitoring procedure is performed; another may be to perform the procedure at home using a remote monitoring device. When we know the cost of treating complications that may occur for a disease, then a monitoring bundle contains all the information necessary to compute the (expected) cost of the treatment of the disease for a patient in a population class over a certain planning horizon. If a monitoring bundle includes one or more procedures that are performed using a remote monitoring device, then the costs of manufacturing the device must be taken into account when costing the bundle. Because the monitoring device consists of a base unit and one or more peripherals, the cost depends on which peripherals are needed to perform the procedures that are done using the remote monitoring device.

From the above discussion, it is clear that it is straightforward to identify for each
population class the bundle that is most cost effective. Note that the current environment, i.e., the one in which no use is made of a remote monitoring device, can be viewed as a monitoring bundle as well.

Next, we discuss three models, each one progressively more realistic to obtain an initial assessment of the societal benefits of remote in-home monitoring devices.

4.1 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**

- \( d_j \): number of patients in population class \( j \)
- \( C_i^j \): cost to an individual in population class \( j \) with monitoring bundle \( B_i^j \)
- \( c_{\text{base}} \): manufacturing cost of a base unit
- \( c_l \): manufacturing cost of peripheral unit \( l \)
- \( c_{\text{direct}}^t \): direct cost of procedure \( t \) for population class \( j \) with use of bundle \( B_i^j \)
- \( c_{\text{loss}}^t \): productivity loss associated with procedure \( t \) for population class \( j \) with use of bundle \( B_i^j \)
- \( c_{jk} \): cost of complication \( k \) for population class \( j \)
- \( p_{jk} \): probability of occurrence of complication \( k \) for population class \( j \) with use of bundle \( B_i^j \)

Recall that a monitoring bundle specified a frequency for each procedure that has to be performed for the patients of the population class and that this frequency is used to calculate the direct cost of the procedure for the planning period. If we assume that the current environment is represented by monitoring bundle 0, then we obtain the following costs:

\[
C_j^0 = \sum_t \{c_{\text{direct}}^0 + c_{\text{loss}}^0\} + \sum_k p_{jk}^0 c_{jk},
\]

and

\[
C_j^i = c_{\text{base}} + \sum_{l \in B_i^j} c_l + \sum_t \{c_{\text{direct}}^i + c_{\text{loss}}^i\} + \sum_k p_{jk}^i c_{jk}
\]

Given the above, the societal benefit of using remote monitoring devices is simply

\[
\sum_j d_j (C_j^0 - \min_i C_j^i),
\]
that is, we identify for each population class the cheapest bundle, compute the savings associated with switching from the current system to using this bundle, and multiply by the number of patients in the class.

Of course, the implicit assumption here is that there are no limits on the number of base units and peripherals that can be manufactured.

### 4.2 Capacitated Model

It is unrealistic to assume that there will be an unlimited supply of base units and peripherals. Therefore, the next model assumes that we know the number of base units available as well as the number of peripherals of each type. (Of course peripherals can only be used when a base unit is present.) In this situation, the problem is not simply one of computing the minimum-cost monitoring bundle for each population class as we may not be able to provide the necessary bundles to each of the patients in the class.

**Data elements**

\[ d_j : \text{number of patients in population class } j \]
\[ C^i_j : \text{cost to individual in population class } j \text{ of monitoring bundle } B^i_j \]
\[ r_k : \text{amount available of resource } k \]
\[ u^i_k : \text{amount of resource } k \text{ used in monitoring bundle } B^i_j \]

We have kept the model general by introducing the concept of resources. Resources in this situation refer to base units and peripheral units.

**Decision variables**

\[ y^i_j : \text{fraction of } j^{th} \text{ population class served by monitoring bundle } B^i_j \]

**Objective function**

\[
\text{minimize } \sum_i \sum_j (d_j \ast C^i_j) \ast y^i_j
\]  

(1)

**Constraints**

\[
\sum_i y^i_j = 1 \ \forall j,
\]  

(2)
\[ \sum_i \sum_j (d_j \times y^i_j) \times u^i_k \leq r^i_k \quad \forall k, \] (3)

Constraint (2) ensures that for each population class \( j \) that all patients are served by some bundle. Recall that the current system, where the monitoring device is not used to perform any procedure, is included as a bundle. Constraint (3) ensures that availability limits are respected. Note \( u^0_k = 0 \) for all resources \( k \).

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, we may also consider the variant in which the \( y^i_j \) variables are restricted to be binary, i.e., in \( \{0,1\} \), in which case a unique bundle will be assigned to each population class.

5 Capacitated Model with Equitability

This model attempts to determine the minimum cost to serve all population classes with bundles given supply limits, i.e., manufacturing capacity constraints, and such that the savings from using remote monitoring devices are divided equitably over the 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.

Data elements

\[ d_j : \text{number of patients in population class } j \]
\[ C^i_j : \text{cost to individual in population class } j \text{ of monitoring bundle } B^i_j \]
\[ r^i_k : \text{amount available of resource } k \]
\[ u^i_k : \text{amount of resource } k \text{ used in monitoring bundle } B^i_j \]
\[ \alpha : \text{maximum difference of percentage savings allowed between population classes} \]

Again, resources refer to base units and peripheral units.
**Decision variables**

\[ y^i_j : \text{fraction of } j^{th} \text{ population class served by monitoring bundle } B^i_j \]
\[ T^j_j : \text{total cost to population class } j \]
\[ v : \text{the smallest percentage savings any population class receives} \]
\[ w : \text{the largest percentage savings any population class receives} \]

**Objective function**

\[ \text{minimize } \sum_j T^j_j \tag{4} \]

**Constraints**

\[ \sum_i y^i j = 1 \quad \forall j, \tag{5} \]

\[ T^j_j = (\sum_i y^i j * C^i_j) * d^j_j \quad \forall j, \tag{6} \]

\[ \sum_i \sum_j (d^j_j * y^i j) * u^k_k \leq r^k_k \quad \forall k, \tag{7} \]

\[ v \leq \frac{d^j_j * C^0_j - T^j_j}{d^j_j * C^0_j} \quad \forall j, \tag{8} \]

\[ w \geq \frac{d^j_j * C^0_j - T^j_j}{d^j_j * C^0_j} \quad \forall j, \tag{9} \]

\[ w - v \leq \alpha, \tag{10} \]

Constraint (5) ensures for each population class \( j \) that all patients are served by a bundle. Constraint (6) calculates the total cost for population class \( j \). Constraint (7) ensures the availability limits are respected. Constraints (8) and (9) computes the smallest and largest percentage savings over all classes. Finally, constraint (10) ensures that the difference between the largest percentage savings and smallest percentage savings is less than a given bound.
6 Computational Study

To illustrate and demonstrate the value and insight the models discussed in the previous section may provide, we have conducted a small, simplified computational study. It is simplified in the sense that we focus on a very small subset of chronic illnesses: diabetes and heart disease. The reason for choosing these two particular chronic illnesses is simple: they affect a large fraction of the population, so even partial and basic insights into the societal benefits of remote monitoring devices for these diseases may prompt intensified efforts to make remote monitoring devices available quickly and broadly, because we expected, rightfully so, that the study would show there are significant societal benefits.

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. Data challenges are a common phenomenon in economic and decision models for health care problems. To account for uncertainty in some of the data, we have decided to conduct sets of experiments in which we use “optimistic,” “expected,” and “pessimistic” values for some of the uncertain data.

6.1 Data

Diabetes is among the most prevalent and costly health problems in the United States (CDC 2005a). Of the 2005 U.S. population of 267 million people, 6.48% have been diagnosed as diabetic (CDC 2005b). Of the diagnosed diabetic cases, approximately 92.5% are Type II and 7.5% are Type I (Harris et al. 1998). In addition, another 8.32% of the U.S. population has been diagnosed as pre-diabetic (Benjamin et al. 2003). Thus, for diabetes three population classes are considered: (i) pre-diabetic, (ii) Type II diabetic, and (iii) Type I diabetic.

Common complications that diabetic patients encounter are blindness due to retinopathy, and cardiovascular disease (CVD). The cost to the diabetic patient due to these complications are $4,700 and $47,240 respectively (Caro et al. 2002, American Diabetes Association 2003). According to Hoerger et al. (2004), the risk of developing blindness due to retinopathy can be reduced from 2.3% to 0.3% by reducing A1C levels. For our study, we assume that this risk reduction can be realized when patients in any of the three population classes utilize the remote monitoring device. The risk of diabetic patients developing CVD
is much higher, as CVD is the cause of death for 65% of all diabetic patients (CDC 2004b). For our study, we assume that this risk can be reduced by 10% for Type I and II diabetic patients. Furthermore, we assume that without the benefit of improved health monitoring using the remote monitoring device, all pre-diabetic patients will become diabetic at some point in time. If, on the other hand, remote monitoring is adopted, we assume that 10% of the pre-diabetic patients will not develop diabetes. Thus, only the remaining 90% of the pre-diabetic patients will develop diabetes and have a 65% risk of dying from CVD. The total risk for CVD of the pre-diabetic class reduces from 65% when the device is not used to 58.5% when it is. These complications, risks, and associated costs can be found in Table 1.

We should mention that other complications could be reduced by home monitoring, and so the results are in a sense a lower bound on the potential benefit. Table 1 shows the number of patients in a population class ($d_j$), the probability of retinopathy with bundle $B_j^0$ and $B_j^1$ ($p_{j1}^0$ and $p_{j1}^1$), the costs associated with retinopathy ($c_{j1}$), the probability of CVD with bundle $B_j^0$ and $B_j^1$ ($p_{j2}^0$ and $p_{j2}^1$), and the costs associated with CVD ($c_{j2}$).

The monitoring procedures we considered for diabetes patients were FPG (fasting plasma glucose), A1C, OPFF, and CBG (capillary blood glucose). These procedures are tests that are performed at regularly specified intervals for diabetic patients. Each procedure is recommended four times per year for each population class, with the exception of the CBG test. It should be performed once per day for Type II diabetic patients and four times per day for Type I diabetic patients. Currently, the CBG test is the only test that is performed at home using a simple testing device.

Each procedure has a direct cost and a lost productivity cost to the patient, which differs depending on whether the remote monitoring device is used or not. When the monitoring device is used to perform the procedures, the direct cost consists of the cost of the non-

<table>
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<th>$j$</th>
<th>Class</th>
<th>$d_j$</th>
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<td>4,700</td>
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<td>0.003</td>
<td>4,700</td>
<td>0.65</td>
<td>0.55</td>
<td>47,240</td>
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<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Type I diabetic</td>
<td>1,905,000</td>
<td>0.023</td>
<td>0.003</td>
<td>4,700</td>
<td>0.65</td>
<td>0.55</td>
<td>47,240</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Hypertension</td>
<td>89,142,857</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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reusable testing supplies. The cost estimates for these supplies are based on those published by Test Medical Symptoms at Home, Inc. (2007) and on figures published in the literature (Zhang et al. 2003, Hoerger et al. 2004). When the procedures are performed without a remote monitoring device, the direct cost consists of the cost of supplies, plus the cost for an office visit. The Medical Expenditures Panel Survey (MEPS) estimates that the cost of an office visit is $160 (American Diabetes Association 2003, AHRQ 2007). Because FPG, A1C, and OPFF are tested with the same frequency, we assume that these procedures will be performed during the same office visit; thus the office visit cost is split equally among the three procedures. Because the CBG test is performed at home, it does not incur an office visit cost. MEPS estimates the value of a one-day loss (or eight-hour loss) of productivity as $168 (American Diabetes Association 2003). We assume that a half hour is lost for each procedure performed in the home, and that a half day is lost for each procedure performed during an office visit. Frequencies and costs for the different procedures can be found in Table 2. The number of times per year procedure $t$ is performed for population class $j$ with bundle $B^i_j$ is denoted by $f_{ti}^j$.

Table 2: Procedure frequencies and costs

<table>
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<th>$f_{1i}$</th>
<th>$f_{2i}$</th>
<th>$f_{3i}$</th>
<th>$f_{4i}$</th>
<th>$c_{0\text{direct}}^t$</th>
<th>$c_{0\text{loss}}^t$</th>
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<th>$c_{1\text{loss}}^t$</th>
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<td>4</td>
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<td>-</td>
<td>61.32</td>
<td>28</td>
<td>8.32</td>
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<tr>
<td>2</td>
<td>A1C</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>-</td>
<td>76.20</td>
<td>28</td>
<td>23.20</td>
<td>10.50</td>
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<tr>
<td>3</td>
<td>OPFF</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>-</td>
<td>70.22</td>
<td>28</td>
<td>17.22</td>
<td>10.50</td>
</tr>
<tr>
<td>4</td>
<td>CBG</td>
<td>4</td>
<td>365</td>
<td>1460</td>
<td>-</td>
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<td>10.50</td>
<td>24.40</td>
<td>10.50</td>
</tr>
<tr>
<td>5</td>
<td>BP</td>
<td>-</td>
<td>-</td>
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<tr>
<td>6</td>
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<td>1</td>
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<td>28</td>
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<tr>
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<td>ECG</td>
<td>-</td>
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<td>-</td>
<td>1</td>
<td>353.00</td>
<td>28</td>
<td>300.00</td>
<td>10.50</td>
</tr>
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</table>

It is estimated that over 65 million people in the U.S. have hypertension using the definition that an individual meets one of three conditions: i) blood pressure of 140/90 mm Hg or higher, ii) using blood-pressure lowering medications, or iii) having been told at least twice by a physician or other health professional that they had high blood pressure (Fields et al. 2004). The estimated prevalence is between 24% and 33% (Burt et al. 1998, Fields et al. 2004). The cost of treating hypertension has been estimated to be $947 the first year of treatment, $575 the second year, and $420 per year thereafter (Odell and Gregory 1995).
Recommended screening for patients with hypertension are: i) a weekly blood pressure check, ii) an annual test to check for blood in the urine, iii) an annual blood test to check cholesterol and glucose levels, and iv) an annual electrocardiogram (ECG) (Caro et al. 2004). The frequencies and costs for the different procedures can be found in Table 2.

Hypertension can lead to complications such as congestive heart failure. Not including productivity losses, the treatment costs alone in the U.S. for congestive heart failure are $25-40 billion annually. The prevalence of congestive heart failure is 1.8% and the annual cost per patient is between $5000 and $8000 (Payne and Caro 2004). Proper screening of patients with hypertension, however, reduces the odds of congestive heart failure by 86% (Payne and Caro 2004). This complication, its risk, and its associated costs can be found in Table 1.

6.2 Experiments

All the experiments conducted involved the four population classes introduced above, i.e., pre-diabetic, diabetic Type II, diabetic Type I, and hypertension. Based on discussions with one remote monitoring device manufacturer, we have set the manufacturing cost for a base unit at $800 and the cost of manufacturing a peripheral at $75.

First, we computed the solution to the basic model. The result provides an upper bound on the societal benefits that can be expected from introducing remote monitoring devices as the basic model is unconstrained and assumes that an unlimited supply of remote monitoring devices is available. In Table 3, the per-person annual cost to each population class using their most cost-effective bundle \((C^*_j)\), the per-person annual cost to each class using the current system \((C^0_j)\), and the associated savings \((C^0_j - C^*_j)\) is shown. Using these savings and the number of patients in each population class, the total annual societal benefit resulting from the use of remote monitoring devices is estimated to be in the order of 1,160 billion dollars, a savings of 43.25%.

Of course, these computations assume an unlimited supply of remote monitoring devices. This weakness is remedied in the second experiment where we use the capacitated model. Because we do not have any information on manufacturing capacity for remote monitoring devices, we have experimented with two supply limits: 50% of the total target population and 25% of the total target population. By doing so, we hope to better understand the impact of manufacturing capacity on the societal benefit, but also the impact on
Table 3: Annual Per-Patient Cost Savings With Basic Model

<table>
<thead>
<tr>
<th>j</th>
<th>Class</th>
<th>$C_j^1$</th>
<th>$C_j^0$</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pre-diabetic</td>
<td>29,135</td>
<td>32,121</td>
<td>2,986</td>
</tr>
<tr>
<td>2</td>
<td>Type II diabetic</td>
<td>40,081</td>
<td>44,720</td>
<td>4,639</td>
</tr>
<tr>
<td>3</td>
<td>Type I diabetic</td>
<td>78,296</td>
<td>82,935</td>
<td>4,639</td>
</tr>
<tr>
<td>4</td>
<td>Hypertension</td>
<td>1,997</td>
<td>13,366</td>
<td>11,369</td>
</tr>
</tbody>
</table>

the allocation of devices to the different population classes.

The results of the capacitated model are not surprising. Table 3 shows that the largest annual per-patient savings are obtained for patients with hypertension. Combining this with the fact that hypertension also has, by far, the highest prevalence of the four diseases we consider (the 89 million patients represent approximately 69% of the total number of patients in our four population classes), the model simply decides to allocate the entire supply of monitoring devices to patients with hypertension in both settings. The resulting savings are approximately 738 billion dollars and 375 billion dollars, respectively.

These results may not be perceived as fair (or realistic) since we are taking a societal benefits perspective. Therefore, we study the impact of equitability considerations. Without any equitability considerations, the model will make decisions purely based on cost considerations and, as we have seen, it may happen that no devices will be allocated to one or more population classes. To avoid a wide disparity in benefits between different population classes, we limit the the difference between the cost benefits of two population classes. For the situation in which the supply of devices is limited to 25% of the population, we experimented with two disparity limits: 10% and 5%.

Not surprisingly, the societal benefits drop again, to roughly 273 billion dollars annually (or a little under 10% savings) with 10% cost-savings equitability, and to 205 billion dollars annually (or a little over 7%) with 5% cost-savings equitability. More interestingly, the allocation of monitoring devices changes significantly. Table 4 and Table 5 show the percentage of patients in each population class that receive a remote monitoring device for both the 10% cost-savings equitable and 5% cost-savings equitable solutions.

Because of the uncertainty associated with some of the data used, especially the prevalence of diseases and the risk reduction for complications when using the monitoring device, we have conducted a variety of experiments aimed at establishing the sensitivity of the
Table 4: Percentage Allocation 10% Cost-Savings Equitable

<table>
<thead>
<tr>
<th>( j )</th>
<th>Class</th>
<th>% receiving device</th>
<th>% not receiving device</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pre-diabetic</td>
<td>45</td>
<td>55</td>
</tr>
<tr>
<td>2</td>
<td>Type II diabetic</td>
<td>74</td>
<td>26</td>
</tr>
<tr>
<td>3</td>
<td>Type I diabetic</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>4</td>
<td>Hypertension</td>
<td>17</td>
<td>83</td>
</tr>
</tbody>
</table>

Table 5: Percentage Allocation 5% Cost-Savings Equitable

<table>
<thead>
<tr>
<th>( j )</th>
<th>Class</th>
<th>% receiving device</th>
<th>% not receiving device</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pre-diabetic</td>
<td>55</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>Type II diabetic</td>
<td>92</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>Type I diabetic</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>Hypertension</td>
<td>12</td>
<td>88</td>
</tr>
</tbody>
</table>

solutions with respect to values for these parameters.

The first set of experiments varies the risk reduction estimates for CVD for the three diabetes related population classes. CVD was chosen because it is much more costly than retinopathy. Values used for the risk reduction parameters were 60%, 62%, 65%, 67%, and 70%. The second set of experiments varies the disease prevalence estimates for the four population classes. Prevalence values were reduced by 10% and 5% and increased by 5% and 10%. (In each of these experiments, we assumed that the supply of devices is limited to 25% of the population and the cost-savings disparity is limited to 5%.)

Somewhat surprisingly, the results varied very little. In all cases, the societal benefits were a little over 7% of the total expenditures.

Overall, the experiments indicate that the broad introduction of remote monitoring devices will provide significant societal benefits.

As mentioned at the beginning of this section, we have conducted only a small, simplified study. The primary reason for the study was to illustrate the use of the proposed models and the type of results and insights that can be obtained with the proposed models. The models can easily be extended to incorporate more detail, e.g., more population classes and more cost components. Other more involved extensions are discussed in the next section.
7 Future Research

We have introduced a model for estimating the potential societal benefits of the introduction of remote in-home monitoring devices and we have performed an initial computational study. There are a variety of ways in which the model can be extended allowing for a more detailed analysis or an analysis with a different focus and perspective. As always, for many of these extensions, the challenges are not the modeling but the data collection. Much of the data that is needed to perform this type of study is hard to obtain.

7.1 Determining the configuration of the base unit and peripherals

We have assumed that the configuration of the base unit and that of the peripherals was known and provided to us. In reality, because many of these devices are still under development, these configurations may not have been determined yet and some flexibility may exist. Of course the first step in determining what functions should be included in the in-home monitoring devices is determining which functions would lead to the largest estimated cost savings. Most likely, these will be the monitoring procedures that have to be performed frequently, are costly, or lead to a large reduction in occurrence of one or more serious, costly complications when the procedures are performed frequently.

7.2 Determining the price of the base unit and peripherals

We have assumed that the base unit and peripherals are sold at cost. This is obviously unrealistic and therefore the model could be extended to include pricing decisions for the device. Of course that requires choosing a perspective. The objectives of the manufacturer and those of government or insurance companies are quite different when it comes to what is acceptable in terms of prices. A decision also has to be made concerning whether or not price discrimination is allowed, i.e., whether different prices can be charged to different population classes.

7.3 Determining who should pay for the device

A related question is who should pay for the in-home monitoring device. Is it the Health Maintenance Organization? Health care providers? The patients themselves? A national survey released by Accenture in January 2003 reports that over seventy percent of those
surveyed think their insurance should cover the entire cost of a home health monitoring device (Mace 2003). Fifty percent would be willing to pay for internet service or some other mechanism to enable data transmission, and thirty percent would be willing to pay a small monthly fee of approximately $20.

The above extensions focus on the various questions that may be of interest when considering the production, distribution, use, and benefits of remote monitoring devices. Other extensions focus on handling the uncertainty in some of the data elements.

7.4 Robust optimization and stochastic programming variants

As mentioned before, many of the data elements in the proposed models are uncertain. The proposed models do not explicitly account for this uncertainty. Robust optimization and stochastic programming provide frameworks for modeling optimization problems that involve uncertainty. Robust optimization assumes that the data elements are known only within certain bounds. The goal is to find a solution which is feasible for all possible realizations in the data interval and optimal in some sense (recent attention has focused on optimizing for the worst-case realization). Stochastic programming models assume that probability distributions governing the data elements are known or can be estimated. The goal is to find a policy that is feasible for all (or almost all) possible data realizations and that maximizes the expectation of some function of the decisions and random variables. In the context of remote monitoring devices the primary uncertain data elements are the probabilities of complications arising for a disease and the prevalence of a disease. Robust optimization or stochastic programming models which explicitly account for the uncertainty of these parameters could provide more accurate and reliable estimates of societal benefits.

References


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http://www.ahrq.gov/clinic/3rduspstf/diabscr/diabcost.htm


