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A Collaborative Awareness System for Chronic Disease Medication Adherence Applied to HIV Infection

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Abstract—**Electronic reminder systems have been available for decades, yet medication adherence remains poor. Most systems rely on simple alarms and do not address other determinants of health-related behavior. This paper describes a collaborative awareness system for chronic disease medication adherence that relies on patient self-reflection and clinician support. Visualizations of adherence performance, including estimated plasma concentration graphs and a dynamic, personalized, disease-state simulation, are available to the patient (cell phone and internet media display) and clinician (computer) in real-time. The clinician can send asynchronous video messages of advice and encouragement to the patient regularly. A pilot was conducted with four HIV positive patients for four weeks. Three patients who started with suboptimal adherence improved (93.0% to 99.1%, 83.0% to 96.3%, and 63.9% to 81.3%). One patient who started with optimal medication adherence (>95%) maintained this level. All four patients appreciated the rich feedback and wanted to continue using the system.**

I. Introduction

Adherence to medications for chronic disease is consistently poor throughout the world. As few as 50% of patients take their medications correctly [1], [2]. Even the most effective interventions have not achieved improvements large enough to significantly affect clinical outcomes [3]-[5].

Human Immunodeficiency Virus (HIV) infection is one chronic disease for which medication is critical but for which adherence remains poor [6], [7]. Most patients achieve about 70% adherence with recent studies reporting between 53% and 83% [8]-[10]. The factors affecting non-adherence are different for every patient case. They include:

- Complexity of the medication regimen - number of pills, administrations a day, and dietary restrictions [11]-[13]
- Occurrence of side-effects [14]
- Patient factors - level of education and literacy, alcohol and drug abuse, depression, childcare duties, economic constraints, and social support [14]-[17]
- Patient beliefs about medication effectiveness [18]

Technological approaches to improve HIV medication adherence have included pagers, alarming pill containers, text messages, and mobile phone applications [19]-[21]. The majority of these systems have taken an alarm-based approach, focusing specifically on the forgetfulness aspect of poor medication adherence. A recent review of all electronic reminder studies concluded that, although individual studies reported some benefit, there was a lack of definitive data about the effectiveness of these devices [22]. On the other hand, systems that provide more education and allow patient reporting have shown promise in improving engagement [23]. Also, adding more personalization has contributed to improved adherence [24]-[26]. Paper-based adherence performance feedback has been effective for other clinical problems but it has not been the focus of electronic systems [27].

While every patient may deal with different factors that affect adherence, a supportive doctor-patient relationship is capable of aiding the patient to overcome many of these factors [12], [28]-[32]. Unfortunately, adherence is not sufficiently addressed by many physicians [29], [33], [34]. This presents an opportunity for improvement in HIV medication adherence, since it is quite possible that this important omission is due to time constraints and lack of effective tools rather than physician disregard.

This report presents a model system for supporting chronic disease medication adherence that aims to engage patients as active participants in their care and to embrace their motivation to collaborate and learn. The philosophy of the system is dramatically different from typical alarm-based reminder systems. It is a collaborative awareness system that makes information about medication adherence available to both the patient and clinician in real-time and at a glance. It establishes a channel of asynchronous communication that allows patients to express their concerns as they arise and clinicians to provide advice and social support at the opportune moments. Dynamic visualizations of the effects of medication on the disease not only allow patients to learn through personal experience, but they also facilitate the asynchronous communication by providing common ground [35]. Although the primary goal of the system is to improve medication adherence, the larger vision is to enable a new paradigm of healthcare delivery that aims to bolster trust and communication in the patient-clinician relationship in order to improve overall chronic disease management, preventative care, and health education.

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II. Methods

A. Collaborative Awareness System Description

1) Collaborative Interface for Medication Scheduling (Clinician's Office): Patients cannot be expected to adhere to decisions that are made without their input. Prior to using the collaborative awareness system, clinician and patient use a touch interface (Fig. 1a) to schedule medications as a shared decision.

2) Daily Medication Clock (Patient Devices): The medication schedule created in the clinician's office is automatically synchronized to two patient devices. They provide awareness of adherence information at a glance throughout the day. An internet media display called a Chumby (Fig. 1b) sits with the patient's medications while a cell phone (Fig. 1c) travels with the patient. Both devices offer additional non-visual awareness. The Chumby plays music that increases in volume as the hour hand moves through an adherence interval. The cell phone plays a tone and/or vibrates each hour during an adherence interval.

3) Adherence Reporting and Performance Feedback: Patients self-report adherence as shown in Fig. 2a. Since patients have difficulty accurately recalling their adherence performance, a detailed record is constantly updated to promote self-reflection and bolster motivation. Not only does it show which doses were administered, it also estimates the plasma concentration of each medication, as illustrated in Fig. 2b and calculated according to the equation in Fig. 2c. Patients are typically told the dosing schedule for a medication without education about its significance because an office visit leaves little time. The plasma concentration graphs, however, provide common ground on which clinicians can teach patients the fundamentals of pharmacokinetics. These fundamentals are reinforced through patient personal experience. If a patient takes two pills once a day instead of one pill twice a day, the medication level will rise out of the normal range and then fall too low later in the day. The patient hopefully develops a deeper understanding of the importance of adherence that affects behavior and improves effectiveness.

4) Dynamic, Personalized, Disease-State Simulation: Potentially the most important component of the patient's medication adherence awareness is a simulation of the disease for which the medication is being taken. A significant problem in chronic disease management is that patients cannot feel the effects of the disease until it is advanced. It is difficult to set short term goals and to appreciate the benefit of adherence. A dynamic, personalized, disease-state simulation can provide an immediate perception of the benefit. It takes concepts that were previously distant and inaccessible and makes them not only concrete but also actionable. Again, the patient is given the opportunity to learn through personal experience rather than through generalizations. An example disease-state simulation for HIV infection is shown in Fig. 3.

5) Medication Adherence Awareness Interface (Clinician's Office): The patient's medication adherence performance is also available in real-time on a collaborative touch interface in the clinician's office. Short video clips can be recorded and sent to the patient's cell phone and Chumby. This allows the clinician to give advice at the opportune time or to provide messages of encouragement when the patient is struggling. It also allows for messages of praise that may help to make optimal adherence sustainable. Although the patient's adherence was shared with a single clinician in this study, patients own and control their data. They could just as easily share their performance with other health professions, family members, or friends in the future. The goal of sharing is to produce social accountability and to improve communication, disease management, and social support.

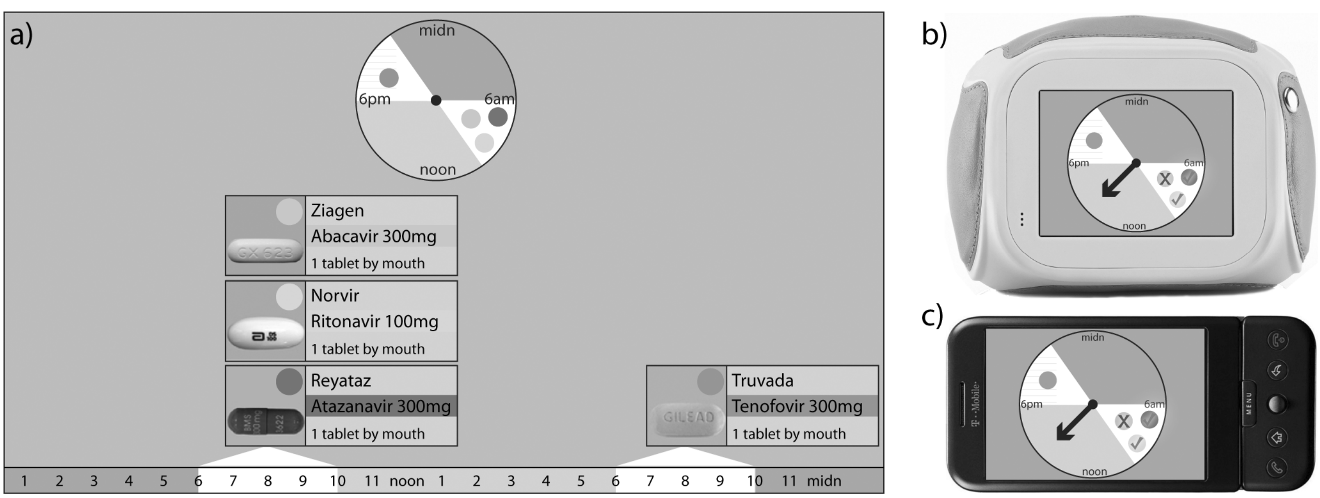
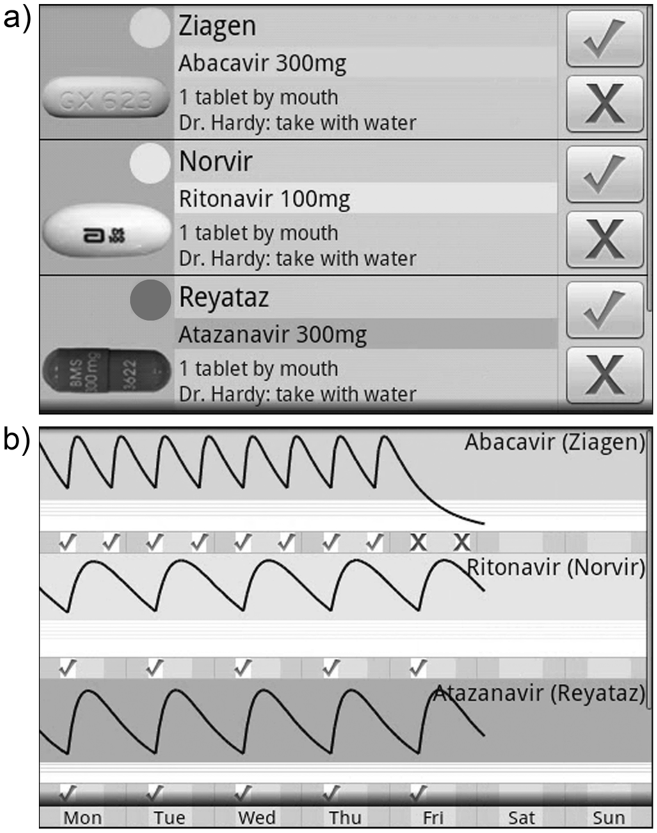


Fig 1. Medication Schedule Interfaces. The patient's medication schedule is created using a collaborative touch interface in the clinician's office, as shown in **(a)**. In this example, the patient has three medications scheduled at 8am with a +/- 2 hour adherence window (white). One medication, Truvada, is scheduled at 8pm. The schedule is changed by dragging a medication across the screen. Adherence windows are adjusted using pinch gestures. The medication schedule is automatically synchronized in the form of a daily medication clock to two patient devices, **(b)** a Chumby and **(c)** a cell phone. Each medication is indicated by a (color-coded) circle. A check mark indicates that a medication has been reported as administered. An x mark indicates that a medication has been reported as not administered.



c)

$$C = \frac{F \times D \times k_a}{Vd \times (k_a - k_e)} \times (e^{-k_e t} - e^{-k_a t})$$

C = Concentration of medication in blood plasma
F = Bioavailability
D = Dose of medication
k_a = Absorption rate constant
k_e = Elimination rate constant
Vd = Volume of distribution

Fig 2. Adherence Reporting and Performance Feedback. Touching an adherence interval in the daily medication clock opens a new view **(a)** that displays an image and personalized instructions for each medication. The patient can press the check or the x buttons to report adherence or non-adherence (with a reason) respectively. If the clinician changes the patient's medication dosage or instructions, this information is not sent via a contextually disconnected e-mail or text message, it is updated directly in this interface. Performing a swipe gesture to the left from the daily medication clock displays detailed information about the patient's adherence performance **(b)**. A separate graph is displayed for each medication. At the bottom of each graph is a bar delineating the days of the week. The white rectangles correspond to each of the scheduled medication adherence intervals. Each of these intervals shows a check mark for reported adherence or an x for reported non-adherence. The black line in each graph is the estimated plasma concentration of the medication. The curve is calculated for each dose using a standard pharmacokinetic equation **(c)**, then all of dose curses are aligned based on the self-reported time of administration and summed (superposition).The solid shaded region in each graph (color-coded) represents the goal concentration. The striped region below that represents sup-optimal concentration. The white region below that represents minimal concentration, such that it can be considered ineffective.

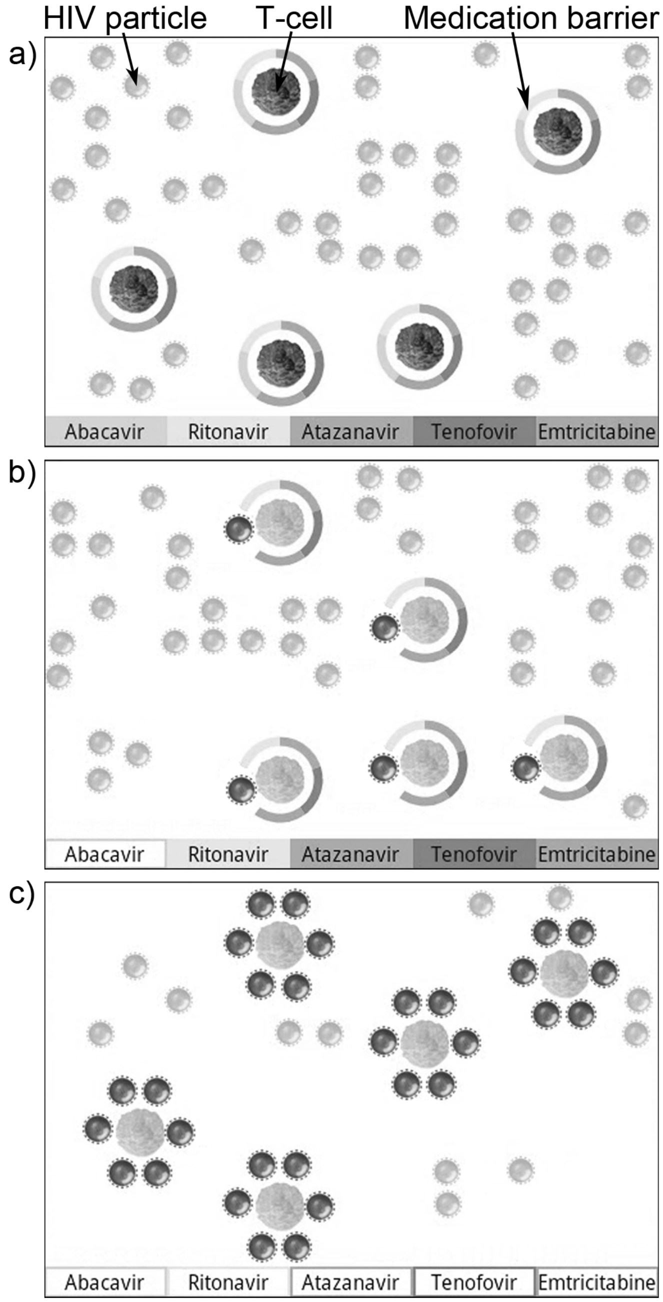


Fig 3. Dynamic, Personalized, Disease-State Simulation for HIV. This simulation represents a drop of the patient's blood. The number of T-cells and HIV particles are proportional to the patient's most recent CD4 cell count and HIV RNA (viral load) blood tests. The dynamics of the interaction of the T-cells and the HIV particles are affected by the patient's medication taking behavior and updated every hour based on the pharmacokinetic calculations in Fig 2c. If the patient maintains optimal medication adherence, as show in **(a)**, all of the T-cells are protected by a barrier that is composed of a (color-coded) segment for each of the medications. If the concentration of a medication falls, as happens in a matter of hours after missing a dose, then the corresponding segment becomes striped and then disappears. Once the segment disappears, the virus can begin attacking the T-cells as portrayed in **(b)**. If all of the medications fall to minimal concentration, then the T-cells become overwhelmed with virus as in **(c)**. The patient can easily restore the protective barrier for the T-cells in a matter of hours by simply taking his or her medications. Note that in the actual simulation, animation is used to convey more information. Protected T-cells move in fluid patterns while T-cells that are getting attacked remain still. Attacking HIV particles move in a rapid vibrating pattern while other HIV particles remain still.

B. Study Protocol

A four-week pilot evaluation of the collaborative awareness system was conducted for HIV medication adherence through the Center for HIV and AIDS Care and Research at Boston Medical Center (BMC). The sample included two males and two females, one Caucasian and three African Americans, with ages ranging from 43 to 61 (mean = 51). All of the patients were of low socioeconomic status but had stable housing situations. All of the patients had a high school education or less. Two patients had experience using cell phones and two did not. None of the patients had experience using a computer.

Each patient came to BMC for a preliminary educational visit with Dr. Hardy as their medication adherence coach and Dr. Moore as a technology instructor. Each patient was able to create his or her medication schedule using the collaborative interface. After the schedule was created, each of patient was given a Chumby and a cell phone with service prepaid (one patient was not given a Chumby because there was not an internet connection available at his home). Each patient was instructed on the use of both devices. Baseline adherence was calculated using pharmacy refill data (# days taken / # days prescribed x 100).

Patients returned to BMC once a week for individualized feedback sessions. During these sessions, pill counts were conducted and study adherence was calculated (# pills taken / # pills prescribed x 100). Self-reported adherence was also reviewed with the patient using a collaborative touch interface and study adherence reporting accuracy was calculated (# correct self-reports / # of self-reports x 100). Between each weekly visit, adherence performance was reviewed by both Dr. Hardy and Dr. Moore. Video messages of support were sent in response to these evaluations. Patients were encouraged to give regular feedback and were given questionnaires (5-point Likert scale) about their experiences after the first and fourth weeks.

III. Results

TABLE I
PATIENT ADHERENCE AND ADHERENCE REPORTING ACCURACY

	Baseline Adherence	Study Adherence	Study Adherence Reporting Accuracy
Patient 1	93.0%	99.1%	100%
Patient 2	83.0%	96.3%	96.3%
Patient 3	100%	96.6%	96.6%
Patient 4	63.9%	81.3%	78.6%

Patients were enthusiastic about the medication adherence system. Questionnaires revealed that all four wanted to continue using the system and all four though that it was helpful in improving their adherence and communication with their health provider. None of the patients regarded the system as an invasion of privacy. In addition, the questionnaires revealed that they all thought that effort of self-reporting medication adherence on a daily basis was commensurate with the value that was provided in return. The value not only included improved adherence and communication but also improved sense of well-being because the system provided them with confidence that they could control the HIV infection.

IV. Discussion

The results from the pilot evaluation of the medication adherence system with HIV+ patients were encouraging. Patients 1, 2, and 4 improved their adherence and were enthusiastic about the new channel of communication with the adherence coach. Although patient 3 had no room for improvement in her adherence, she expressed that she appreciated the sense of control that the system gave her over her infection. She thought that it would help her to maintain optimal adherence (>95%) as it did during the study. (Although the results suggest a slight decrease in adherence for Patient 3, they were interpreted to represent maintenance of optimal adherence since baseline adherence was established using pharmacy refill data, which is typically an overestimate, while study adherence was evaluated using more accurate pill counts.)

The dynamic, personalized, disease state simulation was perhaps the most impactful part of the system. Prior to the beginning of the study, patients were asked how important they thought it was to avoid missing even a single dose of their medication. They typically replied that missing a single dose was probably not significant. When instructed that even missing a single dose could lead to resistance, they still failed to appreciate the importance. After using the disease-state simulation, however, patients would come into the office and apologize immediately for missing a dose. One patient said, "I saw myself getting attacked, and I took my medication right away." The most impressive benefit was that patients then began to ask questions about their disease, including how to prevent spreading it. The virus was no longer a mystery but instead something that they could see and understand. They became active participants in their care and were actively seeking knowledge.

Although the results were encouraging overall, patient 4 did not achieve optimal adherence and also had poor reporting accuracy. She denied having difficulty using the interfaces on the cell phone and Chumby. She provided several possible explanations for her inconsistent pill counts and reporting: (1) She took a number of other medications and it was possible that she sometimes accidentally took a different pill instead of one of her HIV pills. (2) She sometimes reported taking the medication first and planned to take the pills shortly after. She may have subsequently forgotten to take them. (3) In the evenings, sometimes her daughter would hear the music on the Chumby and tell her to take her medication. She might have forgotten to take the medication after her daughter reported it for her. A solution for this patient would be to pair an electronic pill box with the collaborative awareness system. This could help to ensure that the proper pills were being taken and that they were reported only at the time of retrieval.

V. Conclusion

Involving patients as active participants will be fundamental to improving healthcare. This pilot study demonstrates the potential of several new techniques for engaging patients in their care and for teaching them through rich interaction with their data. The next goal is to conduct a study that is scaled to test for statistical significance, that lasts up to a year to test for sustainability, and that follows clinical measures to test for improved outcomes. The collaborative awareness system will also be studied with other chronic diseases and for diet and exercise behavior modification. Customized interfaces and simulations for hypertension, diabetes, asthma, smoking cessation, and obesity are already being addressed. An interactive human is being built so that users will eventually be able to navigate a simulation of themselves from head to toe and from organ system down to molecule, all driven dynamically by their own data. This system will not only support experiential education in patients, but it will continually educate the clinicians who care for them.

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