Monitoring Stress and Heart Health with a Phone and Wearable Computer

Rosalind W. Picard and Charles Q. Du

Heart disease is the number-one killer in the USA, taking three times as many lives as all cancers combined. This paper describes a research project to build a wearable monitoring system that communicates through a Motorola iDEN phone, facilitating active monitoring of heart signal information in healthy people as well as patients with cardiovascular disease. This research could also potentially serve as the foundation for further development of early diagnosis and warning systems for household healthcare. We describe means of sensing, together with means of processing the electrocardiogram (ECG) to obtain information related to stress. The immediate goal is to construct a system that is comfortable, easy to use, and useful in gathering information that may lead to better prevention and care for heart disease, with special focus on factors related to affective states known to impact heart functioning.

Affect and Health

The saying, "if you can't measure it, you can't manage it" may be appropriate for early signs of heart disease. In particular, factors such as stress that play major roles in cardiovascular health have been hard to measure in any precise ongoing way. Many people are unaware of their stress levels and the effects of their emotional states. The issue is complicated by the fact that a certain amount of stress can be healthy—motivating and energizing—as well as too much stress being unhealthy. The "right" level varies with temperament, with task, and with other factors, many of which are unknown.

Presently, there is a lack of data analyzing how stress levels vary for the average healthy individual, over day-to-day activities. We would like to build a device that helps to gather and communicate data for improving an individual's understanding of both healthy and unhealthy stress in his or her life. The device itself should be comfortable to use and should not increase the user's stress. It is noteworthy that stress monitoring is important in human-computer interaction for testing new designs, and may be of increased importance when the design is with the user for extended periods of time, as wearable systems are expected to be [8, 9]. In such cases, detection of stress from the wearer can be used to identify aspects of the system interaction that are in need of improvement.

Stress was found to be the number-one health concern in a recent Blue-Cross Blue-Shield survey across New England. Stress is medically known to directly influence, via hormonal and neuronal pathways, the functioning of the immune system. Although stress itself does not make an individual ill, it decreases immune system functioning in such a way that he or she is more likely to get sick when stressed. Several studies have been conducted examining the impact of stress on immunity. For example, Sheldon Cohen, a psychologist at Carnegie-Mellon University, and his colleagues, exposed 394 healthy subjects to one of five respiratory viruses (and a control group to a saline substitute) after assessing how much stress they were experiencing in their lives. The subjects were then quarantined and monitored for evidence of infection and symptoms. They found a strong ($p<0.005$)

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association between the rates of respiratory infection and increases in psychological stress. Cohen et al. [3] also found that 27% of the low-stress subjects came down with a clinical cold while 47% of the high-stress people came down with the cold. Several other potential mediators of illness, including smoking, alcohol consumption, exercise, diet, quality of sleep, white blood cell counts, and total immunoglobulin levels, as well as several variables of personality related to stress, were not found to explain the association.

Of particular interest is a set of findings where negative states related to hostility—namely, anger, cynicism, mistrust, and aggression—have been linked to heart disease. John Barefoot and colleagues found that in a sample of 255 physicians, those who scored highest on tests of hostility while they were in medical school were seven times as likely to have died by the age of fifty as those who scored low on the hostility tests–their tendency to get angry was found to be a stronger predictor of early death than were factors such as high blood pressure, high cholesterol, and smoking [1]. Williams [13] surveys a number of similar studies, showing evidence that it is not "type A" behavior that is the root cause, but rather the specific negative affective components related to hostility, anger, and cynicism. Similar studies have been conducted that support a relationship between negative affect and death from cardiovascular disease, not only across physicians, but across thousands of other subjects. One of these studies was of a group of 118 lawyers, with a 28-29 year follow-up period after taking the Cook and Medley hostility scale, where scores relating to cynicism, hostile affect, and aggressive response were found to be significantly related to death [2].

McCraty et al. [7] have shown how emotions such as anger and appreciation have significant effects on heart-rate variability, in particular, affecting the sympathovagal balance. While both anger and appreciation increased overall autonomic activation, and both produced an increase in sympathetic activity, feelings of appreciation produced a shift in the amount of energy toward mid- to higher-frequency components of the heart-rate variability power spectrum. Thus, appreciation is believed to lead to a relative increase in parasympathetic tone, as reflected in the heart-rate variability. It is hypothesized that such measurable influences of affect on the heart may be, in part, responsible for some of the influences that states such as hostility have on incidence of heart disease. A system designed to record such changes in the heart while people encounter natural situations that give rise to states such as hostility or negative stress, is expected to be useful for helping gather data to test this hypothesis.

Stress is a general term, and does not have a clearly understood relationship, physiologically, as to how it compares to affective states such as anger: for example, anger tends to involve stress, but stress may also be experienced without anger, and it may affect the likelihood that anger gets triggered. Thus, when one is examining physiological changes associated with affective states, there can be a variety of changes in the body depending on the precise nature of the state and how it was elicited. The device described in this paper should assist in collecting data during a variety of naturally occurring states; thus, it should contribute to basic physiological understanding of how the body changes during such states, as people go about their natural activities. The system is aimed at making it easy to measure physiological changes in the heart related to stress and negative affect, as a person undergoes daily activities. The idea is to use these measurements, along with annotations collected from the wearer, to better manage efforts to prevent cardiovascular disease.

Active Monitoring

One of the important changes taking place in health monitoring is the transition from passive monitoring to active monitoring. By taking advantage of the analysis and communications capability of the mobile platform, a system could take active steps to assist patients, either through performing some local intervention or sending an emergency call. The system currently under development utilizes wireless connectivity and onboard processing to enable active monitoring capabilities beyond the standard systems used by modern healthcare.

Consider this possible future scenario with an active monitoring device:

Morning: Mike showers and before he dresses, he snaps on his health monitor. He grabs a bagel, his briefcase, and his freshly recharged cell phone and runs to catch the train. On the train, he flips open the phone for a quick chat with his Health Expert—"Bud." Bud tells Mike that yesterday's heart stress levels were the best yet—nice and low—except for during the evening, between 5:00 and10:00 PM. He congratulates Mike on his steadfastness with checking in, saying his heart patterns are typical for someone four years younger. He asks if Mike wants to tell about what happened yesterday. Mike says, "No time now; later."

Afternoon: After five hours of meetings, Mike pops open the phone again while he's standing in line to grab lunch, to see how he's doing. Bud says that the morning levels were unusually high–similar to last night. Mike asks to see the graphs, and Bud shows them on the phone's display. Mike says, "Oh, this morning was a meeting with unhappy clients; I just heard about it last night at 5:00PM and had to prepare for the meetings." Bud says, "I will annotate last night and this morning as 'meetings with unhappy clients' unless you say 'no."' Mike says "that's fine" and Bud annotates the graphs. Bud asks Mike if he'd like some 1-minute tips for lowering his stress. Mike says "sure" and Bud walks him through a simple exercise. Mike asks Bud to give him a ring later that night, and then practices this exercise as he walks slowly back to the office. A glance at his phone shows him that it's helping—his stress level has gone down. That afternoon, while dealing with the crisis, Mike remembers how good he felt doing the exercise, and gives it another try.

Evening: On the train home, Bud rings Mike to see if now is a good time to follow-up. Bud shows Mike that he's back down to his previous good level for that time of day. Mike asks Bud to compare today to his worst (most stressful) day. Bud displays a graph from a day labeled "crisis with boss" and juxtaposes this with today's graph. Mike recognizes that he is much more in control of his stress now; he smiles and thanks Bud for the help.

In this scenario, Bud could be a personal digital assistant, specially equipped with interpersonal skills such as the ability to back-off and perhaps even apologize when an action he takes increases your stress. Although Bud doesn't exist yet in an automated interactive form, the system described below is a concrete step toward delivering such possible services.

The current standard procedure for monitoring patients with long-term cardiovascular disorders is the venerable Holter Recorder, developed decades ago. Holters are used to monitor ECG (electrocardiogram, which measures heart electrical activity) or EEG (electroencephalogram, which measures brain electrical activity) and record this activity on cassette tape. Recorded signals are then analyzed off-line using dedicated diagnostic systems after the data is uploaded to a dial-up server. Existing devices mostly record twenty-four hours worth of activity, and data is uploaded all at once through phone lines. New generations of Holter devices have been developed using solid-state memory instead of magnetic tape as the recording medium [5], but with the same analysis overhead and functional limitation to passive observation without the ability to intervene. In addition, all Holter devices are limited in terms of user base due to the fact that its availability is limited to those patients deemed by doctors to be chronically ill. They do not represent the broad spectrum of individuals who may be at risk of cardiovascular disease who would benefit from monitoring and study while they are still healthy.

Many active monitoring systems are currently under development by other researchers. The standard intervention for a heart-attack patient might be contacting paramedic help. Since the vast majority of patient mortality is due to death before reaching the hospital, the overall chance of patient survival could be greatly improved by allowing more patients to get help faster. More specifically related to cardiovascular care is the implantable defibrillator that has recently come into use, which applies shock therapy to the heart in case of trauma [10]. The major contribution of this line of research could be to improve data gathering and processing to a point where problems could be detected before they occur, rather than after, so interventions could be performed.

For healthy patients, there may not be need for such drastic interventions; rather, the device could serve to gather information regarding which affect-related behaviors are correlated with an increased likelihood of cardiovascular disease long-term. Thus, the device's purpose would be to help you become aware of potentially harmful behaviors and take early steps to reduce risk and prevent disease from ever occurring.

Measuring Stress

While there is no definitive, non-invasive method of directly measuring stress levels, one measurement that can be made with multiple potential benefits is the measurement of Heart Rate Variability (HRV), which is calculated from the ECG. HRV varies not only with stress, but also with physical fitness and age [12]. It tends to be greatest in those who are younger, more physically fit, or relaxed. In general, it decreases with age, with declining fitness, and with stress.

HRV is a form of sinus arrhythmia that directly reflects bodily functions. It is typically measured from the power spectrum of the inter-beat intervals, which are derived from thresholding the R-waves of the ECG. In particular, it usually involves windowing the ECG, detecting the beats and computing the inter-beat intervals (IBI's), computing the spectrogram of the time series of these IBI's, and then dividing this spectrogram into low-, mid-, and high-frequency bands, in order to separate relative influences of the baroreflex, as well as the sympathetic and parasympathetic nervous system activation. In fact, the measure we use is not exactly HRV, but related to it, based on a new tool for spectral analysis and taking the entropy of the result.

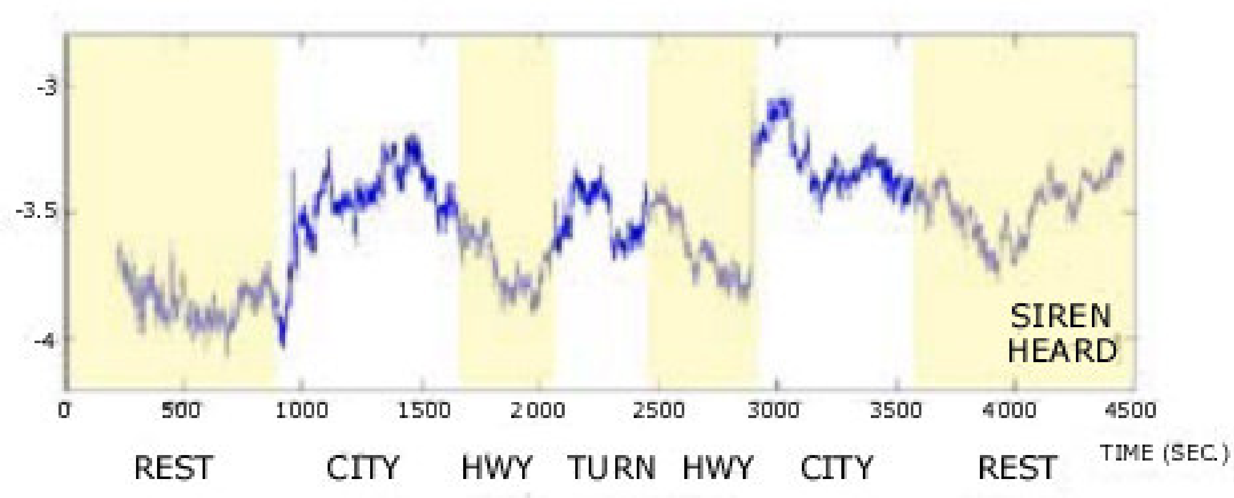

Figure 1: Entropy of heart rate spectrogram for a driver in Boston

For example, Figure 1 shows the output of the new measure for a driver in Boston, given her ECG. She is first resting motionless, with her eyes closed, for 15 minutes while the car is parked in the garage. The level is seen to be low. Second, in the white segment labeled "city," the driver exits the garage and begins driving in Cambridge, with its numerous pedestrians, joggers, and bicyclists, some of whom dart out in front of the car, even when not at intersections. Next, the driver enters the Massachusetts Turnpike, and is instructed to stay in the right lane. Although the speed of the car is higher in this case, the reported stress is lower, since there is no traffic and little to worry about while driving straight. The next white region is where the driver enters the tollbooth and has to turn around to reverse the route. The second half of the route mirrors the first half, with the exception of the final rest period. Although the subject was again sitting with closed eyes, motionless, in a parked car for about 15 minutes, this time there was a sign of increasing stress after several minutes. This event was later noticed to occur coincidentally with the arrival of a loud siren nearby, which may have elicited a feeling of stress simply by the driver listening and imagining what might be happening.

An output like that in Figure 1 is what we hope to be able to show people in a continuous way, with the system described below.

Figure 2: The Motorola iDEN phone and FitSense chest strap, Motohub, and wristwatch.

System Design

Traditional HRV measurement involves an ECG with three or more electrodes and connecting wires, and an A/D converter, all wired to a computer for processing. A problem with the lead attachments is that, after long-term wear, they often result in skin irritation or itching, and the wires could hinder movement. The incorporation of wireless data transfer technology offers the opportunity to make the system more wearable for users. Our main line of research utilizes the FitSense chest strap, a commercially available 2-lead sensor with rubberized electrodes and a small wireless net that is padded for comfort. The chest strap communicates both to the (standard) FitSense watch and (custom) to the Motohub, which plugs into the Motorola phone. The phone acts not only as a display device, but also as a modem, sending data to an off-site location for processing, and for possibly generating the responses of an automatic assistant, and then returning the results to the user via the phone. It is also technically possible for the system to be adapted to display data on other devices, such as a wristwatch, hand-held computer, pager, or even your local refrigerator door with its future electronic display.

Availability is another aspect to which we gave consideration during system design. The major limitation with Holter Recorders and related devices is that they are generally expensive and only useful to individuals with problems, who are then expected to rent or purchase them from healthcare providers. The system that we have put together utilizes commercially available equipment, such as FitSense systems that could be used independently during exercise, and cell phones could be used as regular cell phones when not recording physiological data. The union of the parts simply provides additional functionality: people already carry or wear these devices, and they already know how to operate them.

The system we are developing uses a non-traditional approach to signal processing. Traditional measures of HRV are taken over a long window (typically 15 minutes) of monitoring. The signal processing has required this restriction for getting a good spectral estimate. Traditional algorithms have an awkward way of handling missing data and missed beats, often requiring manual marking of missed beats before processing. Such methods are not real-time. We have developed a new algorithm that appears to overcome these problems: it processes data continuously (avoids windowing), incrementally updates the estimates, handles missing data and noise, and runs in real time. [11]

We have designed multiple interfaces that try to present physiology and affect-related information to people in ways that are informative without increasing stress. The first version of the proposed system would aim to give people access to moment-by-moment stress level, end of day summary (graph, over hours monitored, up to 24) cumulative day summary—for comparing information from day-to-day. The key would be to keep it simple, making it hassle-free to operate, and making the interactions pleasing and informative. Potentially, the system could monitor the user's stress while it is being operated, and see if its own style of operation increases the user's stress, which could then be used to design even more effective interfaces.

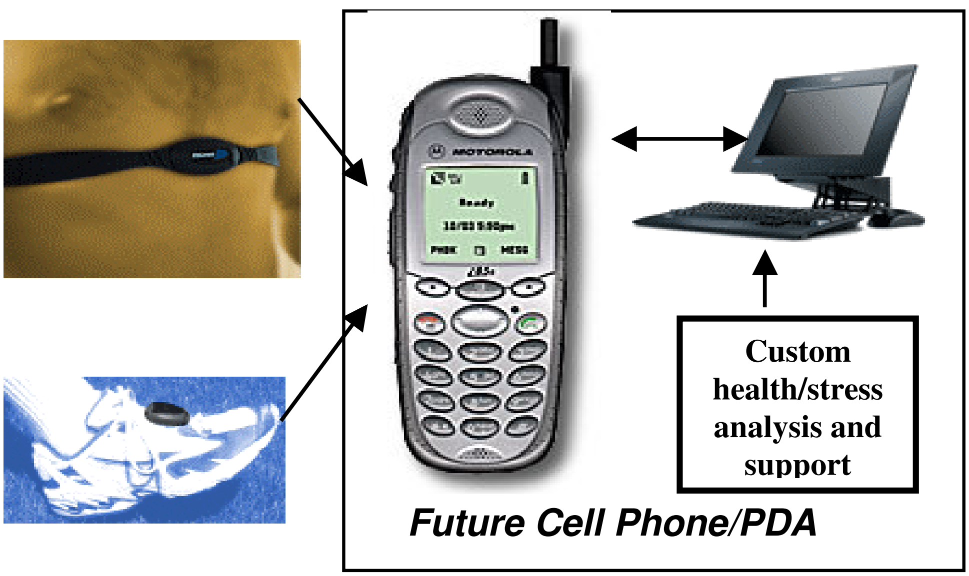

Figure 3: The FitSense chest-strap and foot pod communicate via Motohub to the Motorola iDEN phone, which communicates to an off-body workstation. The workstation can analyze data, make comparisons, and in the future, deliver conversational feedback to support the wearer, or notify medical personnel of the wearer's situation.

System Specification

The system consists of 4 discrete parts: the FitSense sensor suite, including the chest strap, wristwatch, and (optional) an accelerometer worn on the shoe; the FitSense Motohub; the Motorola cell phone; and the PC workstation. The FitSense sensor suite links together at a range of 10 feet through a FitSense RF protocol. The same RF protocol is used by the Motohub to listen to data packet broadcasts from the sensors, and to transmit the data via a serial connection to the cell phone.

The Motohub log memory maintains a 25 record "minute" FIFO log and 10 record "second" FIFO log. Each log can be queried for the oldest record in the log. The Motohub serial interface runs at 4800 baud and responds to a defined set of commands. The Motohub will remain in a low-power state until it is plugged into a cell phone. At that time, the Motohub issues a Hayes AT style command to the cell phone (which acts like a modem). When the Motohub is disconnected from the phone, it again enters the low power state.

Figure 4: The Motorola iDEN phone, i85, which provides the main display and off-body communication and support functions.

The cell phone we are currently using is the Motorola i85, with Web services enabled. The cell phone runs Java and utilizes the Java2 MicroEdition toolkit designed specifically for small mobile platforms. Code is compiled on a PC and loaded onto the cell phone through the iDEN WebJavaApplicationLoader (WebJAL). The cell phone is programmed to accept data from the serial port and send it to the server through its IP connection. It then accepts the PC's analysis results and displays it to the user.

The PC station runs a server application communicating with the cell phone through a common port setting. Data packets are routed through JMatlink to be evaluated with Matlab. The output is then returned to the cell phone. Data inputs to the Matlab code take the form of inverted inter-beat intervals (IBI's) or instantaneous heart rates. Data is output as a measure of "entropy" that we have observed to be high during stressful episodes, and low otherwise.

Discussion and Future Research

The system functions presently for ECG/IBI data collection, for analysis of this data on the PC, and for returning the result and displaying it on the cell phone.

We have some uncertainty remaining regarding the quality of signal we are getting from the FitSense chest-strap as compared to a more traditional 3-lead ECG. The FitSense system guarantees a data point per time interval but this point is the average of the last three inter-beat intervals, which is not yet the accuracy we need. We are in process of developing an interface to the phone for Vadim Gerasimov's Every Sign of Life wearable system, which includes the more traditional electrode configuration [4]. Given that our work has been based on the 2-lead FitSense chest strap system, we would like to test the effectiveness of the modified framework compared with results derived from using a more traditional 3-lead ECG detector. We anticipate that the key difference would be the means by which accurate inter-beat interval data is extracted from the sample data stream, and that the quality of results should be comparable.

Another mild concern is scalability issues with FitSense devices, which require different channel settings to avoid data collision with other FitSense broadcasting devices.

Perhaps one of the most vexing concerns about our system is that the FitSense sensors have the problem that battery power levels are not monitored, so that a system could stop working without warning when the batteries run out. Battery life is also somewhat limited, only lasting up to 48 hours of continuous use in monitoring mode, although this seems to be a general problem for wearable and portable phone systems, unrelated to the specific products here.

There is also a need for more powerful mobile computing platforms, which can take over more of a role in data processing rather than reliance on connection to the off-body PC. The current dependence on constant connectivity also highlights the problems with cell phone network coverage in general. Since construction materials often block cell signals, the resulting "blindspots" may negate some of the benefits of active monitoring. Nonetheless, the extra services available with such a system greatly outweigh the general overall lack of such services without any device.

Later on, we would like people to be able to easily combine the HRV information with annotations they provide (e.g., "meeting with boss") as well as (optionally) with other sensed contextual information (e.g., physical activity data from accelerometers on foot, cell-phone notation that they were making a call, signal from car indicating driving state, etc.) Such annotations could ideally be entered largely proactively by the system, with voice or pen (say on an iPAQ) confirmation by the user. We would like to combine these with supportive feedback that helps the user manage his stress; we have found (in a trial with 70 subjects) that a different system built in our lab [5] can actively help users reduce their frustration level. We think similar techniques may be promising for helping deal with other negative affect states.

Conclusions

The system presented in this paper seeks to facilitate stress data collection with an eye towards improving health and healthcare. Commercially available products were linked together with custom code and algorithms to demonstrate the ability to monitor Heart Rate Variability changes associated with stress. The platform, while still in progress, is flexible enough to communicate with medical caregivers, friends, and counselors, any of whom the wearer might wish to have contact with in a time of needed support. Ongoing research seeks to link comfortably measurable factors related to HRV with health risks and with tendencies to engage in unhealthy lifestyle behaviors such as smoking or overeating. The new approach to data processing and interface usability feedback has the potential to evolve into a system that functions as an accurate and informative health aid for all users.

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Rosalind Picard *MIT Media Lab (Picard@media.mit.edu)* Picard works closely with industry, and has consulted with companies such as Apple, AT&T, BT, HP and iRobot. In addition, she has been a keynote or plenary speaker at dozens of scientific and industry gatherings, and has been featured in national and international forums for the general public, such as the New York Times, Nightline, the BBC, and Vogue. Picard is the author of over 90 peer-reviewed scientific articles on pattern recognition, multi-dimensional signal modeling, and computer vision, and has served as an editor and guest editor for several prestigious publications, such as special issues of IEEE journals.

Picard earned a BS with highest honors in electrical engineering from the Georgia Institute of Technology and was named a National Science Foundation Graduate Fellow. She earned her MS and PhD, both in electrical engineering and computer science, from MIT. She worked as a member of the technical staff at AT&T Bell Laboratories from 1984-1987, designing VLSI chips for digital signal processing and developing new methods of image compression and analysis. Picard joined the Media Arts and Sciences faculty in 1991

Charles Q. Du MIT Media Lab (paladin@media.mit.edu) Du is a Master of Engineering student in the MIT Electrical Engineering and Computer Science (EECS) department who works in Professor Picard's Affective Computing Group. He earned a BS degree in Financial Management from MIT in 2002, and is a candidate for a BS degree in EECS in June of 2003 that is in conjunction with his MEng degree. His research interests include bio-medical engineering, signal processing, systems analysis, and operations research.