HOW WIRELESS HEALTH WILL CHANGE HEALTH CARE DELIVERY

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ABSTRACT

The miniature supercomputer with high resolution screen we carry in our pocket to make phone calls will help bring modern health care to all corners of the world. Instead of building expensive hospitals throughout the developing world, low-cost, high-volume devices wirelessly networked together will help deliver health care to the billions of people who have none today. This application space is rich in opportunities for those who wish to explore new ways of caring for people who today receive little if any medical services. Examples will illustrate how wireless technology and resultant enabled systems will change the way we educate, diagnose, and treat patients throughout the world.

INTRODUCTION

"So many people use apps every day to keep up with their friends, with the news, find out when the next bus will turn up or which train to catch. I want to make using apps to track blood pressure, to find the nearest source of support when you need it and to get practical help in staying healthy the norm"

U.K. Health Secretary Andrew Lansley in Marie Claire magazine.

A typical hospital – complete with power plant, parking, and all expected amenities – in an urban United States (US) location costs approximately US\$1B to build [1]. While this is an affordable investment for a large city in the US, the sum exceeds the 2010 GDP of 22 countries, represents at least 10% of the GDP of 80 countries, and at least 1% of the GDP of 134 countries [2]. Even *one* such hospital represents an unaffordable luxury for the majority of countries worldwide. The US model of health care delivery is simply not scalable to much of the rest of the world.

For many regions, such a hospital-centric model fails due to the lack of infrastructure needed by patients to travel to these centers [3]. As a result, billions on this planet receive little or no health care. In some cases, a health care delivery platform based on cellular technologies competes with nothing but local tribal knowledge. Technology that brings health care to people where they live creates opportunity at many levels, from the individual, through the community, up to an entire country.

At the other end of the economic spectrum, Western countries are bankrupting themselves by delivering health care using models designed when there were few medicines, no sophisticated medical devices, and most people died before they turned 60 years old. Indeed, Western hospitals provide a level of care absolutely unimaginable only a century ago. Advanced surgical tools and procedures, combined with mature imaging modalities including Magnetic Resonance Imaging (MRI), Computerized Tomography (CT), and Positron Emission Tomography (PET) offer to a patient in critical need of care the very highest chances of restoring health.

On the other hand, an increasing portion of Western health care budgets are dedicated to treating the consequences of "affluenza," such as obesity, diabetes, stroke, and heart failure. These diseases persist for years, and the pathways lead to very serious – and expensive – complications. Based on data from the Center for Medicare and Medicaid Studies, it has been estimated that 76% of Medicare spending is on patients with five or more chronic diseases [4]. Unless treated in a nursing home, most patients or their caregivers treat themselves between visits to the physician. It is here where there is an opportunity to improve

health, provide quality care and reduce overall health care costs. For example, a diabetic who changes diet, regularly exercises and takes medicines as prescribed, is more likely to avoid dependency on insulin, become healthier and happier, and consume fewer health care dollars. By providing feedback to patients and their caregivers between physician visits, mobile technology can make an important contribution to Western medicine.

Engineers have been developing sensors to provide such feedback for many years. Blood glucose sensors for diabetes are an essential element in the treatment of that disease. Could other sensor systems make similar contributions to other diseases? Sensing and communication systems based on mobile technology may fundamentally change how individuals interact with the collective knowledge and skills of the modern world when confronted with a medical challenge.

Mobile (wireless) technologies may enable many new models for delivering health care, both in the developed and developing communities around the world. This article discusses how mobile technology will affect three of the most important aspects of health care. The first is education, as sophisticated medical equipment is useless in poorly trained hands and minds. The second is measurement systems, as modern health care often relies upon technology to manage disease. The third is effective and secure use of medicines, as diagnosis is ineffective without valid medicines that are used as prescribed. Furthermore, this article will provide existing and future examples of the use of mobile technology for each of these three aspects of health care, and how they might be used to integrate the developed and developing worlds.

EDUCATION

"Knowledge, therefore, becomes more expensive per unit over time, and the number of units increases exponentially."

"Max Planck pointed out that each unit of new knowledge costs more than the last, because the easier answers come first and give us new techniques to apply to the next"

Donald Kennedy, former President of Stanford University

The Western University Model

Since 1088, when the University of Bologna began a long tradition of education at Western-style Universities, the education system has been comprised of three fundamental elements: teachers who teach, students who learn, and buildings that house them. Of course, there were centers of learning in Ancient Greece, China, Persia, and Pakistan that came earlier in time, but they were organized differently. A European University was comprised of a community of teachers and taught; was granted administrative autonomy from their rulers; evolved curricula; set and reached research objectives; and, perhaps most importantly, granted credentials to those deemed worthy. These centers of learning attracted students and teachers from great distances to a single location. This concentration of people facilitated both the acquisition of "each unit of new knowledge" and the distribution of already-obtained knowledge to the next generation. The "Western University Model" proved to be both productive and effective, and rapidly spread throughout W. Europe in the 11th and 12th Century, E. Europe in the 14th and 15th C, the Americas starting in the 16th C, Australia since the 19th C, and Africa and Asia since the 19th & 20th C.

A strong correlation exists between the date of the first arrival of Western-style Universities and economic progress. While this is not the sole determinant of economic or other success, according to Niall Ferguson [5], the Western Education model is one of the 8 “killer apps” that lead to the success of the “West over the Rest” over the last 500 years. Notably, in Zimbabwe, one of the poorest parts of Africa, the first University was only established in 1952.

So, while the Western Model of Education has served the West and now the Rest well in the past, will it evolve and adapt to the needs and conditions of the modern societies, or will it be replaced by a disruptive solution based on technology? Is the University of Bologna model still the most efficient way of teaching the next generations of students? If one separates the Research function of a University from the Distribution of Knowledge role, one sees that mobile communication systems may replace – or perhaps complement – the campus of buildings. At what point do the taught teach themselves?

African health care by the numbers

The challenge of providing modern health care in Africa is immediately evident upon review of some simple statistics [6][7][8]. While the continent of Africa and its fifty-four countries has the same number of medical schools as the United States, Africa is three times larger in terms of surface area and population. More importantly, GDP per person in Africa (\$1,600) is less than a tenth of the poverty rate in the US (\$22,350).

	United States	Africa
Size	3.79M miles ²	11.7M miles ²
Population	312M	1000M
Per capita GDP	\$47,000	\$1,600
# of medical schools	134	137
Doctors / 1000	2.3	0.27

Table 1: Africa continent of 54 countries compared to US.

Figure 1: Doctors per 1000 people for various African countries.

Many African medical school (and other college) graduates migrate to wealthier countries around the world, leaving a doctor / patient ratio only a tenth that of the US. Think of this as an engineering problem: “How can technology increase the effective number of doctors in Africa by a factor of ten, in less than ten years?”

One approach is to use mobile health to train a much larger number of local health care providers than are currently being educated at the existing African medical schools. Another would be to find a way to encourage those alumni to stay in Africa. A

third avenue would be to create a system where doctors in other parts of the world can have a virtual presence in even the most remote parts of Africa. Mobile Health can play a significant role in all three of these non-exclusive threads.

Topol-Khan Academy

Recently, Eric Topol MD, mused that a medical version of the Khan Academy could be used to help train medical care providers [9]. The Khan Academy (www.khanacademy.org) is a structured on-line education system comprised of over 3000 video lectures covering topics ranging “from arithmetic to physics, finance, and history and 315 practice exercises.” The system has served individuals interested in learning specific skills as well as assisting classrooms achieve their academic goals while allowing each student to advance at an individual pace. For this latter case, higher level summaries of student performance help teachers focus their class time on specific topics that are giving individuals particular difficulty. The Khan Academy is currently being used on comparative basis in a Los Altos, CA, school district to measure its relative performance with the pre-existing teaching methods.

Could a medical version of the Khan Academy be used to train medical practitioners in the developing world using wireless systems that convert a village hut into a medical school? While this might seem far-fetched, an on-line search reveals this telling note posted on The Student Doctor Network:

“Khan Academy

So i noticed that these are great videos for physics chem and bio...does anybody know of any good sites for OCHEM....i have to take this mcat June 17...and I just want to clarify a couple of things in orgo...

In fact, medical students planning to take the MCAT’s are already using the Khan Academy. What is to stop such a network from teaching an entire generation of medical students in, for example, Africa? Skeptics might argue that while the Khan Academy approach could teach Organic Chemistry, it couldn’t possibly teach surgery, or other skills of the profession that are best learned as an apprentice. This may be true for many branches of medicine – for now. On the other hand, could something like Topol-Khan significantly increase the effectiveness of existing medical school programs in Africa? Could it teach pharmacists how to diagnose malaria or worms and sell a prescription? Could one be taught how to use the mobile technologies described herein and elsewhere to provide health care where there is none?

Mobile phones and tablets are being adopted in even the most remote corners of the world. The distribution of knowledge is extremely valuable to everyone, closely following food and water in the pyramid of fundamental needs and wants. The increasing affordability of cell phones and tablets connected to the internet has enabled these technologies to become one of the most popular means of distributing knowledge. Clearly, something like a Topol-Khan Academy could make an important complement to any mobile sensing instrument by giving local people the knowledge and skills to use such tools effectively.

International Medical Schools

The US graduates about 20,000 doctors per year. If all of these doctors left the US and went to Africa, in one-hundred years Africa would have the same number of doctors per 1000 people as the US today. Of course, relatively few American-trained doctors practice medicine in Africa; a much higher percentage of African-trained doctors make the opposite journey. One way of retaining and attracting additional people to Africa is to provide

complementary sources of income for trained people residing in Africa. One way of doing this would be for trained staff in Africa to perform and get paid for some of the routine analyses needed in high-cost regions of the world.

Training African doctors to analyze the diseases of Western patients may seem counter-intuitive – even nonsensical, as many people default to the opposite mental model of how the West will help Africa: have local, untrained, unskilled people take pictures of skin rashes or collect information of the symptoms of disease, and send them through e-mail or text messages to a trained professional in America, who will diagnose the underlying condition. While such model would certainly attract a number of highly altruistic doctors in the West, it would be hardly sustainable: who would *reimburse* our doctors to perform such services for poor people in Africa? Even wealthy Americans can hardly afford the services of their own physicians, let alone patients in the developing world. Instead, more practical and scalable might be the model where an African doctor with one electronic eye and ear in America and both feet in Africa, multiplexes between diagnosing and treating local people while earning a reasonable fee for performing analytical services for high-cost Western hospitals. Even if the number of remote analyses an African doctor made per week is very low, being part of a Western medical system would bring tremendous advantages to that doctor's local practice: knowledge, prestige, and income. Today, it is routine for many American hospitals to send radiographs to qualified Radiologists in India for reading and interpretation. Could South Africa become the site where such a model *goes viral* in Africa?

The cost of an iPad is about \$500 – about one-third of the per capita GDP of Africa. In the right hands and as a component of a formal training process, it could become a critical tool in educating a continent full of doctors. Yet by itself it would be inadequate: the iPad cannot teach surgery or anesthesiology, or can it?

Perhaps a hybrid model of medical school education and practice may arise in the developing world. Those disciplines that can be taught and practiced using mobile technology will blossom, while centers with “big iron” capital equipment will be required for those systems that cannot be “mobilized.”

A hybrid solution such as this provides a “St. James Bible” opportunity for those in the business of educating the next generation of medical students: the teaching materials created over the next few years may be used to educate millions of doctors who treat billions of patients. Similarly, medical devices developed as accessories and add-ons to a cell phone or tablet could both enable this process and service entire continents of people.

Imagine a consortium of the best medical schools each “adopting” an African medical school. Each paired with a bio-engineering department that designs mobile medical systems defined through these interactions. If such noble efforts were coordinated and became part of formal training programs based on a Topol-Khan Academy model, could they produce – within one person's lifetime – a cadre of self-sustainable doctors in Africa capable of providing care to all of its citizens?

MOBILE MEASUREMENT SYSTEMS

"Engineers who are great in physics and calculus but can't think in new ways about old objects are doomed to think in old ways about new objects"

John Ratzenburger, paraphrasing a Stanford study

In this section, we will look at some examples of how various organizations are beginning to use wireless technology to deliver health care outside of the clinic or hospital. With thousands of health-related apps available on smart phones, where does one

start? A cursory review finds many examples of information tools, but fewer, though much more interesting, apps that make the smart phone an essential element of a medical device. A sampling follows of mobile health innovations that promise improvement in quality, accessibility, and affordability of care in an era of increasing need and increasingly constrained resources. Mobile health care technology is just beginning to become a common adjunct to diagnosis, therapy, and management of care.

mHealth Alliance

The mHealth Alliance was launched by the UN Foundation, the Rockefeller Foundation, and the Vodafone Foundation in 2009 to promote the use of wireless technologies in the delivery of health care. Each year, mHealth Alliance sponsors an Innovator's Challenge. The 2011 winners represent their sampling of who is innovating in this space (from www.mHealthAlliance.org):

Mobile system that facilitates pregnancy surveillance, registration and emergency response (Alain Labrique for mCare)

Mobile technology that reduces child mortality (Ann Roos-Weil for Pesinet; Mali).

A personalized voice-based information retrieval and transaction system (Ashok Jhunjhunwala for Voice Net; India).

Field-portable microscope and diagnostics tools (Aydogan Ozcan; Africa, South America, and South Asia).

Instant drug quality verification system via text messaging (Bright Simmons for mPedigree; Africa and South Asia).

A localized multimedia (Derek Treatman for CommCare Sense; India).

Doctor directories and bulk SMS system (Eric Woods for MDNet; Ghana and Liberia).

SIM card applications the least expensive phones (Isaac Holean; Malawi and Cameroon).

Automated phone calls and SIM message system (Joaquin Blaya for MiDoctor).

SMS-based mother and child tracking system (K.S. Shankar ; India).

Clinical decision-support system (Martin Were for AMPATH; Kenya).

Medic Mobile

MedicMobile creates technology that converts \$15 cell phones into extensions of existing open-source platforms, including FrontlineSMS, OpenMRS, Ushahidi, Google Apps, and HealthMap . These SIM apps enable a broad range of sophisticated tools to manage a wide range of health care delivery. MedicMobile.org lists: “community health worker coordination and management, community mobilization for vaccination and satellite clinics, logistics and supply chain management, referrals, routine data collection, and mapping of health services.”

A six-month pilot program in Malawi saved the clinical staff 1,200 hours and over \$3,000 in motorbike fuel. 100 patients received treatment for tuberculosis after their symptoms were communicated using text messaging.

In the developing world, lack of infrastructure prevents health workers from delivering efficient healthcare to rural areas. Networking together very inexpensive phones using easy-to-use, meaningful software is establishing mobile technologies as the platform upon which other services will be built.

Sense A/S blood pressure measuring patch

The Danish company Sense A/S develops ContiPress™, an adhesive patch worn on the arm that continuously measures the patient's blood pressure. The ContiPress™ patch includes electrodes, electronics, and a wireless communication system. The

unit monitors and stores information about the patient's blood pressure over 24 hours, which can be used to aid in the diagnosis of related conditions.

Figure 2: Estimating Blood pressure by measuring impedance.

Head Ballistocardiogram and Head ECG

Under the direction of Prof. Sodini, researchers at MIT have been developing portable sensors that measure both the ECG and Ballistocardiogram. Such novel metrics delivered in a wearable form-factor may provide new approaches to managing chronic disease [10].

Figure 3: Head-mounted ECG / BCG system

Low-cost, cell-phone powered stethoscope ideal for remote care

Originally intended as a way of diagnosing tuberculous pericarditis, this mobile stethoscope kit created by Oxford University and University of Cape Town allows a remote physician access to the acoustic information detectable by a stethoscope using a low-cost cell phone [11].

Figure 4: Recordable stethoscope networked with low-cost phone

The device could be used not only in the direct diagnosis of diseases, but also as a training tool. In-training clinicians could diagnose with a traditional stethoscope and use this device to confirm; recordings could be used as part of a Topol-Khan Academy program to rapidly teach the proper use of a stethoscope.

Smart phone microscope

Researchers at the University of California at Davis have demonstrated a low-cost add-on to a common smart phone that converts the camera into a microscope [12]. This is accomplished through the wise placement of either a 1 mm diameter sapphire ball lens or a GRIN lens placed over the imaging lens of the phone.

Figure 5: Micrographs of blood smears taken with smartphone

In addition, they have developed software that corrects the distortion inherent in this optical system to provide images good enough to take pictures of with a field of view of approximately $350 \times 350 \mu\text{m}$ with $1.5 \mu\text{m}$ resolution.

This technology could be rapidly distributed in rural places to diagnosis various blood diseases. In the above images, normal blood (left panel) is compared with iron deficient anemic blood (center panel), and with sickle cell anemic blood (right panel). Local clinicians could be trained to interpret these images and they can be easily sent to a medical facility for confirmation.

Portable ECG using cell phone

A number of organizations are developing or introducing cell-phone-based devices that use dry electrodes on the phone or its sleeve to detect and record an ECG. Examples include the EPI Life by Ephone International.

Figure 6: ECG using the EPI Life cell phone.

Portable Ultrasound using cell phone

GE and Mobisante both recently announced portable, low-cost ultrasound devices that may replace the stethoscope in many clinical settings. One barrier in the West is *reimbursement*: would each use of a \$5,000 device deserve the same fee derived from much more expensive systems? In Africa, this lower cost and portability could lead to *Médecins Sans Hôpitals*.

Figure 7: Portable ultrasound.

Apple Computer

Apple Computer recently announced a security configuration that would make the now-ubiquitous iPad HIPAA-compliant [13]. Healthcare providers now can use the FaceTime video chat function to securely talk to patients and other clinicians. Regulatory compliance provides entree to Western health care, but the marginal utility of such a system is much higher in Africa.

SECURE AND EFFECTIVE USE OF MEDICINES

"Drugs don't work in patients that don't take them"

C. Everett Koop

Secure packaging counters counterfeit drugs

Drug counterfeiting is an estimated \$75 billion business in 2010, and fake medications are responsible for at least 700,000 deaths every year [14][15]. Malaria medication is especially at

risk; according to the World Trade Organization, fake malaria drugs kill 100,000 Southeast Asians a year [14].

A new system from HP and mPedigree assigns a code that is revealed by scratching off a coating on the packaging of participating drugs. This code can be text messaged by the consumer at the point of purchase to a free SMS number to verify the authenticity of the drug package. If the drug package is real, the patient receives a reply of "OK," and other information like the expiration date. If the drug packaging contains a counterfeit code, the consumer receives a message alerting them that the pack may be a fake, as well as a phone number to report the incident [15].

Unfortunately, this system validates the package of the medicines, and not the medicines themselves. The Healthstore Foundation, a non-profit founded in 1997 to create self-sustaining pharmacies in developing nations and with which the author was once affiliated, provides a stable, sustainable supply of genuine medicines to rural, under-developed regions. (76 pharmacies were established in Kenya by the end of 2010, serving about 500,000 patients.) One common counterfeiting method was documented by a sting operation performed by Glaxo-Smith-Kline: good medicines are first emptied from authenticated packages, which are then refilled with counterfeit medicines and resealed to look like genuine, authentic packages [16]. Thus, authenticating drug packages and not the medicines themselves may provide a false sense of security. Nevertheless, this appears to be the best available system to counter the sellers of counterfeit medicines.

Digital Medicines

The author and other researchers at Proteus Biomedical have developed a digital health feedback system comprised of a wearable sensor, an ingestion sensor and a viewing application [17]. The "MEMS" contribution to this system is a silicon chip coated with CuCl and Mg on opposite surfaces that is embedded in each tablet or capsule. Upon digestion in the stomach, the two dissimilar materials combine with the stomach juices to power up the CMOS circuit. The circuit, in turn, modulates the current between those two materials and thus the rate of reaction of $Mg \rightarrow Mg^+$ and $Cu^+ \rightarrow Cu$. This modulation of chemical reactions allows information to be communicated from the ingestion sensor to the wearable sensor.

Figure 8: Digital medicine system used to manage chronic disease

The initial use will be a digital health feedback system that helps a patient manage chronic disease by providing feedback of their medicine ingestion, activity rate, heart rate and similar indicators of their health. Many medicines do not achieve their full therapeutic value when used outside of a hospital simply because

they are not ingested as prescribed. The entire disease category of XDR TB (Extremely Drug Resistant Tuberculosis) is caused simply because patients do not follow a full course of inexpensive antibiotics, allowing resistant strains to evolve and multiply. Examples of effects of poor adherence in the treatment of heart failure, mental illness, diabetes, oncology, and organ transplant are found throughout the medical literature [18][19][20].

An illustrative example of how the Proteus system may be used is the treatment of diabetes. There are three therapeutic pathways to treat a pre-insulin-dependent diabetic: diet, exercise and medicine. By far the most common prescribed medicine for diabetes is generic metformin. Proteus' health management system will directly measure two of these three categories: exercise and digestion of "digital" metformin.

But tracking data is only the beginning. Closing the feedback loop is crucial and can be achieved by sharing of the data with friends, family members, physicians, pharmacists (more common in small towns and in the UK than in urban US) or other diabetics.

Games will be set up allowing individuals or teams to get fun feedback for healthy behavior. For example, a patient might sign up for "MedMatch™", where each time a patient ingests a digital medicine, a pill is donated to an individual in Nairobi. A program might be geared toward Breast Cancer survivors who today walk or run in fundraising "marathons." This "game" would track their heart rate and step count during the event and their taking of prescribed Tamoxifen between fund-raisers; the "teams" with the highest adherence between fundraisers might win awards such as having their photos taken with athletes like Lance Armstrong, himself a cancer survivor, at the next fundraiser. This way, the fundraisers are helping themselves while they are raising funds to finance research that helps others.

Figure 9: Digital medicine system used to fight counterfeit drugs

Another important use of Proteus' digital medicines will be to give pharmacists the ability to validate the integrity of their medicines – before selling them. The prototype shown in Figure 9 is targeted for use in the developing world, where the dongle detects the chip inside the pill and communicates its ID to a central database using the phone. The approach would be robust against even the most committed counterfeiter, who today re-packages useless medicines into valid packages.

SUMMARY

The application of mobile technology to health is still in its infancy. Cell phones that record ECG's, listen to heart-beats, take

micrographs of blood smears, measure blood pressure and blood glucose levels, are only the tip of the spear that will lance disease in places that today have little access to modern medicine. iPads may open a new window on how the next generation of doctors will be trained and serve in both the developed and developing regions. It is a realm full of opportunity for those who build systems that measure, detect, sample, or otherwise sense. The collision between miniaturization and health care creates an opportunity to help build electronic bridges between continents of people, and make lasting impact on the upward march of humanity.

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