mHealth: unbiased signals – open & affordable healthcare tech in a resource constrained-world

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The global problems with healthcare

- **Too few trained medical professionals**
  - With poor communication & often physical infrastructure / equipment

- **Spiraling costs**
  - Ageing populations & chronic disease epidemics
  - Increased awareness of diseases - obligation to treat
  - Increased demands for ‘heroic’ interventions
  - Lack of preventative measures / compliance
  - Increased complexity of treatments & diagnostics
    => more infrastructure & training

- **Lack of portable longitudinal medical records**
  - (& portability), access to information (& data)

- **Too much ‘data’, too little information**
  - We’re being swamped by noise
  - But noise is information too

- **Humans are fallible (medical errors)**
And it’s going to get worse... with lots of people on earth

Country area is proportional to proportion of world population that live there (7bn)
World map area is proportional to # births
(Over 7bn people now – populations expanding quicker in poorer regions)
Too few medical experts available

County area is proportional to relative # physicians
Patient:Doctor Ratio

China 950:1
Central Africa: 50,000:1

http://bigthink.com/ideas/21237
Health Care spending Per Person 2007

• Per capita health care spending in poorer countries is ~100 times lower than higher GDP countries
• Healthcare quality is not a function of spending
• WHO rankings
  – US 37th (Costa Rica is 36th !)
  – Germany 25th
  – Canada 30th
  – UK 18th
  – Mexico 61st
  – China 144th
  – India 112th

The poorest have the worst deal!

http://www.photius.com/rankings/healthranks.html
Technology & Infrastructure in Resource-Poor Settings for Health Care

- Old legacy hardware & instruments
- Generally paper notes, static information – no QA!
- Poor communication channels
- Poor drug storage and supply
- Poor waste disposal
- Poor transport
- Intermittent electricity
- Information shortage
- Skills shortages

Poor infrastructure

- Relative proportions of global landline telephone faults 2002
Ad-hoc medical facilities

- Free-market without regulation / standards
- Out of calibration, incorrect supplies, little training
Leapfrog Healthcare

• An opportunity exits to redefine healthcare delivery!

• Basic issues: **diagnosis, treatment delivery** (supply chains) and **compliance**

• Long-term cry in development: Why can only Coca Cola manage to deliver everywhere?

• Not true anymore: Mobile phones are everywhere

• **Mobile phones solve the supply chain issue!**
  - Almost ubiquitous, peer-to-peer sales
  - People want & maintain them (unlike medical devices)
  - Cheapest method for transmitting and recording information to and from remote locations
  - *Information is the key* – longitudinal medical records & telemedicine
Recent trends (2010-2011)

- CM projects **957 million** Mobile Internet users: 2014

- Android handset sales grew **886%** worldwide during 2010. (The **739 million** mobile users in China, >98% coverage (889m in 2011, 800m in India)

- **277 million** Chinese accessed the Internet through mobile devices in June 2010 (up 18.4% in 6 months!)

- China is 3G, India went 3G this year. (closest competitor – the iPhone - only grew 86% in the same period.)

- So - not one laptop per child, but **one mobile phone per human?**

Ref: Briefing: Mobile Communications, MIT Technology Review Vol 113, No. 6, Nov/Dec 2010 pp 67-75  (Canalys estimate)
Other problems with healthcare

- **Equipment is expensive and complex to use**
  - Yet we don’t have population or individual-specific algorithms
  - Too much focus on reactive not proactive medicine
  - Overly sensitive and under-specific
  - Proprietary or poorly described formats & standards
  - Poor service industry to support the devices

- **Currently we under-sample human physiology**
  - Temporally: No idea what happened to patients in the golden hour, before admittance, or after discharge. (In ICU <1/hour)
  - Spatially: What is a normal pattern of exercise for an individual?
Example: BP Aliasing

- **BP**
- **SBP**
- **DBP**

**Treatment threshold**

**24hr mean**

**4am**  **8am**  **2pm**  **10pm**  **4am**

- **Treat**
- **Do not treat**

**24hr mean**
Example: BP Aliasing

![Graph showing BP over time with treatment threshold and 24hr mean values.]
Example: BP Aliasing

BP

Treatment threshold

Treat

Do not treat

4am  8am  2pm  10pm  4am

time
Other problems with healthcare

Sampling modalities are ‘dishonest’

• We lie to ourselves and doctors
  – Humans are poor-self reporters (bad memories / drugs)
  – Embarrassed to admit poor behaviours to doctor

• Humans are inconsistent & make dangerous errors
  – Natural variation, fatigue, distractions, Friday afternoon syndrome …
    • Mistyping / wrong units (overdose / drug interactions)
    • Using the wrong patient history (allergies)
    • Errors of omission – forgetting to order drugs
Human Computation is key

- Any single human will make mistakes ~20% of the time
  - But 2 independent humans – 90% accuracy
  - And 3 independent humans – 95% accuracy

- Solution? Crowd Source through mobile phones / Internet
  - E.g. TxTEagle

- Interestingly, humans do not have to be experts, just independent
  - Must make sure humans do not collude!
    (Loudest voice / strongest bladder bias)

- But even then, there are not enough semi-trained ‘experts’

- So we must train algorithms to provide medical diagnostics
  - Algorithms can be combined with humans for ‘committee of experts’
How? Use an open infrastructure

- Use the mobile phone network to connect patients, healthcare workers, pharmacists and doctors
- Log all **transactions** to **track behaviour**
- **Learn patterns** in data
- Provide automated or semi-automated analysis to augment experts
General phone interface

- Authentication of patients (barcode)
- Longitudinal medical record
- Drug lists and previous encounters
- Allergies, preferences
- Customised logic lists for decision support
- User alerts for appointments, diagnoses

http://sanamobile.org
Secure asynchronous connectivity

- Any data type upload (images, ECGs, voice notes, text, ...) via https
- Bandwidth sense, data packetized
- Data unpacked on backend server
- Passed to open source medical record
- Multiple doctors informed data is ready for diagnosis
Multiple-expert review

- Data reviewed by multiple independent experts = unbiased accurate labels
- Extensible and generic architecture with few barriers to adoption
- Rapid sampling of population - provide immediate feedback, reduced aliasing
- Easy to train algorithms to replicate experts in many scenarios

Open source backbone - A Vital Feature!

Only way to integrate different devices, and medical data.

Lowers cost of adoption and updates
Opportunity: Scalable Healthcare Through Health Apps

• If we can develop accurate health apps and low cost medical devices:
  – Consumers will pay for automated diagnosis
  – They can pay more for a remote diagnosis
  – And even more for a second or third opinion
  – We can collect the multiple expert annotations
  – …. And improve the product

• Doctors can deal with difficult cases
• … and audit the data and ensure integrity
• Multiple experts ensure higher accuracy
CheapPhones or SmartPhones?

- In last year:
  - iPhone sales up 86%
  - Android sales up 886%

- Most of Android growth in lower-income countries (even Africa)

- Android handset price down from $500 to $100 in 3 yrs

- Power of processor increasing

- Standardized hardware (USB)

- Bootleg Nokia Phone in China only $14 -- smart & cheap!
Smart phones, dumb (cheap) peripherals

- Use as much deployed equipment as possible
- Consumers / patients have already bought most of the device!
- The key is *information* processing
  - Signal Processing and Machine Learning for automated or semi-automated medicine
  - Algorithms to screen quality of data at source
  - Intelligent UI to help user collect better data
General design process for affordable healthcare technology

- Minimal electronics (use phone sensors if possible)
- Offload processing to the phone – computation is then free
- Secure upload of data for multiple (unbiased) expert review and longitudinal medical record
- Train algorithms to diagnose
- Untrained user learns about illness from phone
- Eventually user (patient/HCW) develops intuition about their health conditions

Human & Machine Reinforce Each Other
How do we implement?

- Top-down system design doesn’t work

- Design for a specific problem (bottom-up)
  - Choose a specific partner & location
  - Work out what their needs are & current cultural practice
  - Design around their needs

- But build in enough flexibility to allow integration with other projects!
  - Open API
  - BSD-like Open Source – No vendor lock-in
What health problems should we address (first)?

• By 2030 the global burden from communicable diseases, maternal & nutritional conditions with halve (40% →20%)

• 66% will likely be from non-communicable disease (across all income groups globally)

• 9 of the 10 top burdens on our healthcare systems in 2030 are likely to be noncommunicable diseases

• Chronic diseases are going to cripple the healthcare system

The global burden of disease & injury

WHO: In 2030 Disability-Adjusted Life Years (DALYs) lost will be:

- Chronic diseases are the real issue! How do we manage them?

<table>
<thead>
<tr>
<th>Disease or injury</th>
<th>As % of total DALYs</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower respiratory infections</td>
<td>6.2</td>
<td>1</td>
</tr>
<tr>
<td>Diarrhoeal diseases</td>
<td>4.8</td>
<td>2</td>
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<tr>
<td>Unipolar depressive disorders</td>
<td>4.3</td>
<td>3</td>
</tr>
<tr>
<td>Ischaemic heart disease</td>
<td>4.1</td>
<td>4</td>
</tr>
<tr>
<td>HIV/AIDS</td>
<td>3.8</td>
<td>5</td>
</tr>
<tr>
<td>Cerebrovascular disease</td>
<td>3.1</td>
<td>6</td>
</tr>
<tr>
<td>Prematurity and low birth weight</td>
<td>2.9</td>
<td>7</td>
</tr>
<tr>
<td>Birth asphyxia and birth trauma</td>
<td>2.7</td>
<td>8</td>
</tr>
<tr>
<td>Road traffic accidents</td>
<td>2.7</td>
<td>9</td>
</tr>
<tr>
<td>Neonatal infections and other</td>
<td>2.7</td>
<td>10</td>
</tr>
<tr>
<td>COPD</td>
<td>2.0</td>
<td>13</td>
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<tr>
<td>Refractive errors</td>
<td>1.8</td>
<td>14</td>
</tr>
<tr>
<td>Hearing loss, adult onset</td>
<td>1.8</td>
<td>15</td>
</tr>
<tr>
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<td>19</td>
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E.g. 1 Low Cost Blood Pressure Monitoring

WHO: Ischemic Heart Disease – predicted to be 2\textsuperscript{nd} largest global burden of disease & injury by 2030

: Cardiovascular Disease – predicted to be 3\textsuperscript{rd} largest global burden of disease & injury by 2030

- Phone trains user and feeds back progress/quality reports
E.g. 1 Low Cost Blood Pressure Monitoring (EWH Prize Winner 2011)

- $1 pressure sensor, device fits in tic-tac box
- Flip open to insert USB (power and communication)
- Phone or other device process pressure & calcs BP & HR
- Data uploaded to central server
E.g. 1 Low Cost Blood Pressure Monitoring (EWH Prize Winner 2011)

- Simple to use, no costly parts ($5 for everything)
- Phone trains user and feeds back progress/quality reports
- Can be used in conjunction with CVD screening tools for lifestyle adjustment
E.g. 2 ECG on a mobile phone
(PhysioNet/CinC Competition 2011)

WHO: Ischemic Heart Disease – predicted to be 2\textsuperscript{nd} largest
global burden of disease & injury by 2030

- 1500 12-lead ECGs collected in the field
- Annotated by two trained novices.
  - Expert adjudicated differences
- Signal quality indices calculated on each channel of data
- Neural net trained on 1000 ECGs to classify the other 500 as clinically useful or not
- Accuracy: 99%/95% train/test (highest score in PhysioNet Competition 2011, Sept 19\textsuperscript{th})
- Currently working on implementing neural net on phone for auto-screening
- Then automated & semi-automated diagnostic systems can be added
E.g. 3: Hijacking the phone for auscultation (with T. Brennan - Vodafone funded in SA)

- Use powerful audio processing on phone to capture and analyze breath & heart sounds
- Signal quality measure developed to assess if data is clinically useful, or recapture needed.
E.g. 4: Sleep structure and OSA

Application requires no extra sensors.

90% accuracy in detecting OSA
E.g. 4: Sleep structure and OSA

**Application** Android

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Block diagram describing the phone application system. Acc: Acceleration, Ques: Questionnaire, Bd Ps: Body Position.
E.g. 5: Respiratory Function / COPD

WHO: COPD – predicted to be 5\textsuperscript{th} & Lower Respiratory Airway Infections – predicted to be 6\textsuperscript{th} largest global burden of disease & injury by 2030
E.g. 6: Mental Health

WHO: Depression – predicted to be 1\textsuperscript{st} largest global burden of disease & injury by 2030

- Earliest warning sign of schizophrenia in teenagers is poor sleep & circadian disruption
- Look for unusual circadian activity or desynchronization between different physiological variables
Spontaneous cessation of breathing
Leads to diving reflex …
Drop in HR, BP then later, O2
(watch filter delays though!)
But poor respiratory signals lead to too many false alarms

E.g. 7. Neonatal Apnea

(John Fell Fund, UK)
Global Maps: Infant Death 2001

• # of all infants (<1yr) who died in 2001. [WHO’s ‘Burden of Disease Estimates’, published in 2006.]

For further information on these mortality estimates (first made for 1999), see http://whqlibdoc.who.int/hq/2001/a78629.pdf
Desaturations trigger apnea alarms in NICU monitors

- Over 80% of alarms not clinically relevant
- Desensitisation of staff
- Earlier response needed
- Possible organ damage

Our objective: to reduce the number of false alarms by using multiple sources of data: ECG, PPG, respiration (IP)
Physiological features

- 20 variables computed every 5 s for 300 s pre-desat interval based on:
  
  **Heart rate**          **Oxygen saturation**
  
  **Respiration Rate**    **Signal Quality Indices**

[Graphs of Respiration, Heart Rate, Blood Pressure, O2 Saturation]
Machine learning for classification

- Dataset divided into training and test sets:
  - **training**: 14 stays, 157 positive and 663 negative events
  - **test**: 13 stays, 185 positive and 645 negative events

- Each variable was evaluated at its optimum time interval over complete set of 20 features

- discover optimal subset of features

- RBF SVM trained and tested considering all the possible combinations of features
Points to note

- **Classification accuracy of 100% in training & 90% in test**

- Best results published so far

- Best combination of features is application specific – must be learned from plenty of data

- Fused respiration rate and SQI indices provide supplementary information on top of HR and O2 sat

- Data fusion of multiple sensors and algorithms important
So what?

• We can reduce false alarms by 90%! So down from 82% to ~8%!

• Phone can act as an interventional stimulus:
  • Vibrate,
  • Audible alarm,
  • Message to parent / caregiver

• Mothers can sleep through the night, - device will sensitively and specifically alert them
Prototype:
- Android / USB
- Web connected
- Cost = $15 (Simple circuit/sensors)
Potential Futures?

• Introduce more sensors into phone
  – +$1 for the pressure sensor – many applications including wind speed, lung capacity, weight, etc.

• Partner to collect & analyse medical data
  – Electronic Medical Records
  – Screening for Chronic Conditions
  – Compliance and ‘Honest Signalling’
  – Crowd Sourcing / Intelligent Algorithms
Thank you for your attention

• Questions?
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• PhysioNet / Computing in Cardiology prize 2011 for ECG analysis system on mobile phone ($600)

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