Mobile Device for Disease Diagnosis and Data Tracking in Resource-Limited Settings

Curtis D. Chin,1† Yuk Kee Cheung,1† Tassaneewan Laksanasonpin,1 Mario M. Modena,1 Sau Yin Chin,1 Archana A. Sridhara,1 David Steinmiller,2 Vincent Linder,2 Jules Mushingantahe,3 Gisele Umviliyihozo,4 Etienne Karita,4 Lambert Mwambaringwe,5 Sarah L. Braunstein,5,6 Janneke van de Wijgert,5,7 Ruben Sahabo,8 Jessica E. Justman,6,8 Wafaa El-Sadr,6,8 and Samuel K. Sia1*

BACKGROUND: Collection of epidemiological data and care of patients are hampered by lack of access to laboratory diagnostic equipment and patients’ health records in resource-limited settings. We engineered a low-cost mobile device that combines cell-phone and satellite communication technologies with fluid miniaturization techniques for performing all essential ELISA functions.

METHODS: We assessed the device’s ability to perform HIV serodiagnostic testing in Rwanda and synchronize results in real time with electronic health records. We tested serum, plasma, and whole blood samples collected in Rwanda and on a commercially available sample panel made of mixed antibody titers.

RESULTS: HIV testing on 167 Rwandan patients evaluated for HIV, viral hepatitis, and sexually transmitted infections yielded diagnostic sensitivity and specificity of 100% and 99%, respectively. Testing on 40 Rwandan whole-blood samples—using 1 μL of sample per patient—resulted in diagnostic sensitivity and specificity of 100% and 100%. The mobile device also successfully transmitted all whole-blood test results from a Rwandan clinic to a medical records database stored on the cloud. For all samples in the commercial panel, the device produced results in agreement with a leading ELISA test, including detection of weakly positive samples that were missed by existing rapid tests. The device operated autonomously with minimal user input, produced each result 10 times faster than benchtop ELISA, and consumed as little power as a mobile phone.

CONCLUSIONS: A low-cost mobile device can perform a blood-based HIV serodiagnostic test with laboratory-level accuracy and real-time synchronization of patient health record data.

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In resource-limited settings, the rapid adoption of mobile phones has enabled remote communication of voice and limited data at a low cost. Such mobile technologies are beginning to be used to improve public health and patient care (1, 2); examples include text messaging for improving adherence to malaria (3) and HIV treatment (4, 5), transmission of images for tele-microscopy (6), and personal digital assistants for collecting laboratory results (7). However, there are major areas of healthcare services—including preventive diagnostics—that remain unavailable to patients in remote settings. Ideally, these services would also be linked with mobile technologies that could access health records and hence provide a full context of patient history. Reflecting the view that access to patient records has the potential to markedly improve patient care, over 2 dozen countries in the developing world are implementing electronic databases that collectively contain hundreds of thousands of patient records (8, 9). Rwanda alone has over 90 000 HIV/AIDS patients for whom care is currently facilitated by electronic records (10).

A handheld device that could perform laboratory-quality diagnostic tests and access patient health records (11, 12) would be valuable for many reasons (13), including improved monitoring of disease out-
breaks (14), rapid transmission of field results to health experts, increased effectiveness in allocating medications to different communities (15), immediate treatment or quarantine of patients in difficult-to-reach settings, and reduction in human-caused error in data transcription for health records. Previously, we showed how a low-cost microfluidics test, with no external instrumentation other than a syringe, could perform a heterogeneous immunoassay similar to an ELISA in resource-limited settings (16). A limitation for this previous setup was that a trained user was needed to run the test, interpret the signal, and record the results. Until now, it has remained unclear if an automated mobile device could be built that could run a sophisticated laboratory assay and be inexpensive and robust enough to achieve an impact in resource-limited settings. We aimed to show that all the essential functions of ELISA, the gold standard for detecting many protein biomarkers, could be engineered into a compact device that required no previous laboratory training of the user, similar to a glucose meter, and that consumed as little power as a mobile phone. This mobile device was designed to wirelessly synchronize with a central electronic server to transmit blood test results collected in settings with or without access to cell-phone towers, by using data formats compatible with standard electronic health record keeping.

We sought to use the device for HIV testing in vulnerable populations located in settings without access to diagnostic services. We focused on a mobile device for HIV-antibody detection, among other possible markers for initial testing, for 3 reasons. First, HIV antibody is a widely accepted marker in resource-limited settings, with well-defined clinical management algorithms depending upon the diagnostic result (17, 18). Second, current rapid tests have substantial room for improvement in performance, e.g., the ability to detect weak-positive results (19, 20), objectivity of use by eliminating subjective user interpretation of band intensities (21), and easy linkage to patient records. Third, adoption of a mobile device that performs an HIV immunoassay, a test already familiar to field workers, could promote adoption of other "lab-on-a-chip" tests in the future for other disease markers.

Materials and Methods

OVERALL DESIGN AND DEVICE ENGINEERING

We designed a handheld device, which we call the mobile microfluidic chip for immunoassay on protein markers (mChip) device, that captures the essential functions of ELISA as performed by pipetting robots, microplate readers, desktop computers, and communication hardware, all without the need for grid-based power and at sufficiently low cost and energy consumption to be suitable for resource-limited settings (Fig. 1). The device includes components for liquid handling, signal detection, and remote data communication, which are powered by a single 9-volt battery (Fig. 1, A and B) and controlled by an 8-bit microcontroller and a custom-designed circuit (see the Supplemental Data that accompanies the online version of this article at http://www.clinchem.org/content/vol59/issue4/). For data communication with a remote server, we incorporated 2 wireless technologies: a satellite transceiver for global coverage and a Global System for Mobile Communications (GSM)/General Packet Radio Service (GPRS) transceiver for local cell-phone towers. The choice and design of materials, form factor, and user interface (i.e., a single-button casing with results displayed on a liquid crystal display) were based on surveys of clinical and laboratory workers in Rwanda, as conducted with an industrial design partner (Fig. 2A; see also the online Supplemental Data).

POWER CONSUMPTION AND CONTROL OVER FLOW RATE

Automation of a handheld device that is simple to charge and use (like a mobile phone) could be a major step toward usability and rapid adoption of medical devices in resource-limited settings. To estimate power consumption, we measured the current drawn from the device during an HIV immunoassay on whole blood (Fig. 2B; also see the online Supplemental Data). The single component that consumed the most power was the diaphragm pump. To drastically minimize the power consumption of the device, we designed a vacuum chamber that was connected to the pump and a tunable vacuum regulator; this setup conserved energy by minimizing the time the pump was turned on. The mean power consumption per test, including wireless data transmission, was 0.62 W, comparable to a mean power consumption of 0.75 W for a mobile phone and much less than the 20–60 W required for a laptop computer (22). All the incubation and washing steps of a benchtop ELISA were accurately replicated in our mobile device, as shown by a complete mChip device run in only 17 min on a whole-blood sample with known HIV-positive status (Fig. 2B).

Flow rates in microfluidic systems can affect assay performance (23). In benchtop ELISA, control of incubation times, volumes, and mixing is achieved by pipetting robots. In this device, we could adjust the strength of the vacuum pump in the device to precisely control the flow rate in the microfluidic card from 2.5 to 20 μL/min (see the online Supplemental Data).

TRACnet AND MOBILE COMMUNICATION

TRACnet (www.tracnet.rw) is a PEPFAR (President’s Emergency Plan For AIDS Relief)-funded health-monitoring network in Rwanda hosted by the telecom-
Fig. 1. Overview of the mChip device.
(A), Images of benchtop equipment for an ELISA vs an mChip device, a handheld instrument that performs all essential functions of an ELISA, namely signal amplification and detection, automated delivery of multiple biochemical reagents, and data processing and communication. The image of the mChip device shown here includes a cassette inside. (B), (Left) Inside view of the mobile device, with 3 main modules for liquid handling (orange), signal detection (red), and data communication (green). All modules are controlled by an 8-bit microcontroller along with peripheral components packaged onto a printed circuit board (PCB); (right) illustration of the microfluidic cassette, with areas for reagent storage, sample metering, analyte capture and detection, and waste storage. At the time of assay, a fingerprick of blood is collected in a capillary tube (connecting regions of reagent storage with biochemical analysis) and drawn through the cassette by vacuum generated by a micropump. Sample and reagents are eventually collected and stored as waste in a membrane filter. (C), Comparison of features of a benchtop ELISA (a relatively inexpensive semiautomated setup) vs rapid test (a collection of WHO-approved tests) vs mChip device. In the mChip device, fluid handling, signal detection, and data communication via satellite and SMS are integrated in a device which takes up less space, consumes less power, costs less, and requires less sample and reagent volume than benchtop ELISA. Additionally, the mChip device cost per test compares with cost per rapid test, but allows an objective interpretation of result and can communicate with EMRs. Cost per test for the mChip device is anticipated market price based on sales volumes of millions per year (similar to rapid HIV tests). LCD, liquid crystal display. 9V, 9-volt; NA, not applicable.
munications company Voxiva. It allows healthcare workers using mobile communication such as interactive voice recording to track the health status of over 90,000 HIV/AIDS patients at 295 health facilities offering antiretroviral treatment in Rwanda (10). To demonstrate the ability to transmit diagnostic results to this network database without interfering with live data, our device transmitted test results to a separate demonstration version of TRACnet (see the online Supplementary Data).
Although satellite transmission is traditionally considered expensive, our data transmission requires only short data strings; hence, we used the inexpensive short-burst data service (24) with the Iridium satellite service to ensure global data coverage for our device at a similar cost as short message service (SMS) messages via a cell-phone network (around 10 cents per test result, depending on the network provider). To minimize the size of data to be transmitted, we formatted all the data, including date/time of test, patient’s information, and test results, into short binary strings (see the online Supplemental Data). The data transmission was secure (see the online Supplemental Data).

DIAGNOSTIC EVALUATIONS ON SERA/PLASMA AND WHOLE BLOOD

For HIV testing on fingerprick volumes of serum/plasma (Figs. 3 and 5), we used procedures for surface treatment and reagent loading in PE tubing as described previously (16). The online Supplemental Data contains all details on methods of assay preparation, format, operation, data and statistical analyses, and rejection criteria. For HIV testing using fingerprick volumes of whole blood (Fig. 2B and Fig. 4), we preloaded reagents on the cassette instead of in plastic tubes. For each run, the intensity of the silver film could be interpreted by eye as positive or negative, as in current rapid tests for pregnancy or HIV. The absorbance of each zone was objectively measured by the device (Fig. 3E). Similar to the design of commercial immunoassays, we used a negative reference zone for monitoring nonspecific background signals, as well as a positive reference zone for monitoring gold–silver enhancement (by detecting gold-labeled secondary antibodies), and in some experiments, a second positive reference zone for ensuring sample integrity (by detecting human IgG antibodies). For each data set, the signal was determined by measuring the absorbance of each zone (either on its own or normalized to the positive reference zone), and a cutoff value was chosen to balance diagnostic sensitivity and specificity on the basis of analysis of its ROC curve (see the online Supplemental Data). Signal-to-cutoff ratios were plotted for each data set. To analyze the effect of using different cutoff values, we plotted ROC curves and calculated the area under the curve for each experiment. To determine the statistical robustness of the diagnostic sensitivity and specificity estimates, we calculated 95% CIs (see the online Supplemental Data). Each test, starting from initial handling of the sample to the digital display of results or remote receipt of results, took <20 min.

All work in Rwanda was approved by the Ministry of Health in Rwanda. We tested 167 archived sera/plasma collected from Projet San Francisco and Projet Ubuzima, both of which are nongovernmental organizations located in Kigali, Rwanda, respectively (Fig. 3). Samples from Projet San Francisco were from couples seeking HIV voluntary counseling and testing, and samples from Projet Ubuzima were collected from high-risk women (most self-identified as sex workers) participating in a separate HIV incidence study (25). In addition to HIV serostatus, samples from Projet San Francisco were tested for hepatitis B virus (HBV) and HCV, and samples from Projet Ubuzima were tested for syphilis and herpes simplex virus 2 (HSV-2) (see the online Supplemental Data). We also tested whole blood samples validated for HIV at Muhima Hospital, a district-level hospital in Kigali, Rwanda, which does not perform ELISAs and relies solely on rapid tests for diagnosing HIV (Fig. 4). Whole-blood samples were collected by venipuncture from patients recently presenting to the clinic for antenatal care, voluntary counseling, and/or HIV/AIDS testing. Over the span of 2 weeks, we tested 40 patient samples, of which 26 were positive and 14 were negative, based on sample availability from patients recently presenting to the clinic (see the online Supplemental Data). In addition, for each whole-blood sample tested at Muhima, we attempted wireless data transmission with both satellite and SMS.

We also tested 25 plasma samples from a commercially available HIV mixed-titer panel (SeraCare PRB204) (Fig. 5). For each sample, the supplier provided reference results from ELISA (reported as signal-to-cutoff values) and from 5 commercial rapid tests (reported as positive, negative, or indeterminate). The Abbott HIV-1/2 ELISA test was chosen as the reference HIV antibody test because it produced the most accurate results, as determined by the supplier’s confirmatory assays (26). We interpreted test results to be weakly positive if they exhibited signal/cutoff values between 1.0 and 10.0 on an Abbott HIV-1/2 ELISA test (which has a range of 18.0) or between 1.0 and 2.0 on the mChip device.

Results

Current HIV rapid tests could produce inaccurate results for patients with viral hepatitis infections (27, 28) or sexually transmitted infections such as syphilis (29, 30) and genital herpes (31). To explore the performance of the mChip device on such coinfect samples, we evaluated the HIV accuracy of the mChip device on 167 Rwandan patient samples: 100 plasma samples from Rwandan patients who were also tested for HBV and HCV at Projet San Francisco, as well as 67 serum samples from patients who were also tested for syphilis and HSV-2 at Projet Ubuzima (Fig. 3). Despite the high prevalence of viral hepatitis (99 positive for HBV and/or HCV) in the sample set.
Fig. 3. Performance of HIV immunoassay on the mChip device on Rwandan sera and plasma samples (n = 167) with a range of clinical statuses for viral hepatitis and sexually transmitted infections.

(A), Schematic of HIV immunoassay on the mChip device and the biochemical reactions occurring after the passing of reagents. Four zones are individually treated with proteins: BSA for internal negative reference, HIV antigen for capturing anti-HIV antibodies (Ab), antigoat antibody for capturing gold (Au)-labeled goat antibodies for internal positive reference, and anti-human IgG antibody for capturing human IgG antibody for second internal positive reference. Sera/plasma samples with known HIV status are loaded along with washes and Au-labeled antibodies in tubes (see the online Supplemental Data). (B), Table listing number of truly HIV-positive and HIV-negative samples which are positive (pos) or negative (neg) for HBV and HCV, and the number of truly HIV-negative samples which are positive or negative for syphilis and HSV-2. (C), Vertical scatter plot of the mChip device signal-to-cutoff ratios (S/Co) for HIV-positive and HIV-negative samples. (D), ROC curve, with dashed line as random guess and reported area under curve (AUC). (E), mChip device detection zones, absorbance values (optical densities), and S/Co values for samples with positive, negative, and weak positive HIV serostatuses.
and the substantial number of sexually transmitted infections (31 positive for syphilis and/or HSV-2), the diagnostic sensitivity of the mChip device was high (100%, 86.8%–100.0%), as was the diagnostic specificity (99%, 95.0%–99.8%), with 2 false positives (Fig. 3, C and D). For calculating 95% CIs, we used binomial proportions, a more exact method than the normal approximation. The WHO has recommended the normal approximation for evaluating new diagnostic tests (32) and used them in evaluations of HIV commercial tests with data sets of similar sample size and performance (18, 33, 34). With the use of the normal approximation, the CIs for diagnostic sensitivity and specificity in this data set were 98.8%–100.0% and 98.0%–100.0%, respectively. The ability of the mChip device to objectively measure absorbance values minimized variability in user interpretation of positive and negative results (Fig. 3E).

Fig. 4. Performance of HIV immunoassay on the mChip device on whole blood samples (n = 40) in Rwanda. (A), Schematic of HIV immunoassay on the mChip device and the biochemical reactions occurring after passing of reagents. Four zones are individually treated with proteins, with BSA for negative reference, HIV antigen for capturing anti-HIV antibodies (Ab), and antigoat antibody for positive reference. For each test, 1 μL of whole blood was drawn into a capillary tube and connected to a cassette preloaded with washes, gold (Au)-labeled antibodies and silver enhancement reagents. (B), Vertical scatter plots of the mChip device signal-to-cutoff ratios for whole blood samples positive and negative for HIV. (C), ROC curve of results shown in (B), with reported area under the curve (AUC). (D), Completed (filled bars) and not completed (open bars) transmission of HIV results via satellite and SMS. For each sample tested, we attempted data transmission with both modes (see Materials and Methods for further information). (E), Comparison of data transmission via satellite network vs SMS. Asterisk (*) denotes mean cost per message sent by SMS across different US carriers. (F), HIV results, communicated remotely, are uploaded and displayed in the secure, private demonstration version of the TRACnet system (http://www.tracnet.rw) (see the online Supplemental Data). These results can also be automatically and instantaneously updated onto a global map upon each successful data transmission. A red icon (denoted with a “+” sign) and a blue icon (denoted with a “−” sign) represent positive and negative tests, respectively.
Fig. 5. Performance of HIV immunoassay on the mChip device on a commercial plasma sample panel with low and high antibody titers (n = 25).

(A), Signal-to-cutoff values of the mChip device for samples from a HIV mixed-titer panel (Seracare PRB204), which are classified as positive (pos), weakly positive (weak pos), or negative (neg) on the basis of signal-to-cutoff values from a leading HIV antibody ELISA (Abbott HIV-1/2). For the mChip device, we considered weak positives to have signal-to-cutoff values between 1.0 and 2.0, and for the Abbott HIV-1/2 considered weak positives to have signal-to-cutoff values between 1.0 and 10.0. (B), ROC curve for a mixed-titer panel with a dashed line as a random guess and reported AUC. (C), Table comparing the mChip device, Abbott HIV-1/2 ELISA, and rapid tests on samples. Interpretations of HIV status from ELISAs and rapid tests were based on results supplied by Seracare. Red indicates discrepancy in rapid test result with the Abbott HIV-1/2 ELISA.
Many technologies work well in a laboratory but not in resource-limited settings, which exhibit additional complexities not replicated in a research laboratory, such as local pathogen strain and unexpectedly limited infrastructures (32). When we tested our device in Rwanda on 40 whole-blood samples from patients presenting to Muhima Hospital as part of their routine healthcare for HIV testing and monitoring, we observed that the diagnostic sensitivity and specificity (with 95% CIs) of our point-of-care (POC) device in classifying the HIV status were 100% (86.8%–100.0%) and 100% (76.8%–100.0%) (98.8%–100.0% and 98.3%–100.0% using normal approximations of CIs), respectively (Fig. 4, B and C).

At the end of a test, the mobile device was designed to transmit the test result, encoded into a small data packet, from any remote setting to a central computer server. Via satellite, the data were sent to a predesignated e-mail address along with the global position coordinates of the test; via SMS, a message with the data was sent to a predesignated phone number. In our trial at Muhima Hospital, the device successfully sent results either through satellite or SMS for all samples tested (Fig. 4D). The device successfully transmitted 38 of 40 test results by use of GSM, with the failures presumably due to high traffic in the cell phone network. Also, 33 of 40 test results were successfully sent by satellite, with the failures presumably due to poor weather conditions resulting in unclear line of sight of the sky. Because the satellite module demanded more power and relied on fair weather conditions to send messages successfully, we envision the satellite system as a backup in the event of cell-phone network failure. In contrast to the cell-phone network, the satellite system potentially allows us to send results from every region of the world (Fig. 4E), independent of local cell-phone carrier identity or extent of coverage. The complete test record was uploaded and displayed within a secure section of the TRACnet electronic patient health records database (see the online Supplemental Data). The time-stamped and geolocation-tagged diagnostic results could be easily displayed on a map in real time (Fig. 4F).

Previous studies have shown that rapid tests often fail to correctly identify weakly positive samples (19), such as those from recent HIV infections, which can constitute 0.3% to 3% of HIV-infected patients in high-risk populations with patients seeking care for bacterial sexually transmitted infections at sexually transmitted disease clinics and patients reporting fever in areas of high HIV prevalence (35, 36). Furthermore, rapid tests operated in resource-limited settings have exhibited lower accuracy due in part to the difficulty in interpreting weak signals (18, 19). In quality assurance evaluations across 4 sub-Saharan African countries implementing rapid HIV test programs, concordance between on-site rapid testing and reference laboratory retesting (using primarily ELISA and also repeating rapid tests) among HIV-positive samples was as low as 82% (21). We tested the mChip device on a commercial panel of 25 mixed-titer plasma samples whose reference results had been established at Seracare and at internationally recognized noncommercial reference laboratories (Fig. 5). In this panel, none of the commercial rapid HIV tests, including 2 rapid tests that are currently recommended for HIV screening in resource-limited settings (21), achieved 100% accuracy compared with the Abbott HIV-1/2 (Fig. 5C); patients with such rapid test results would have been classified as “HIV negative” in a screening situation without laboratory ELISA or Western blot experiments. By contrast, using any reasonable cutoff values that did not compromise the diagnostic specificity of the test, as shown by the ROC curves in Fig. 5C, the HIV test results obtained by the mChip device were in agreement with those by the Abbott HIV-1/2, including accurate detection of weak-positive samples (Fig. 5, A and C). Overall, the data suggest that the HIV immunoassay on the mChip device can detect weakly positive samples missed by rapid tests currently used in HIV test algorithms for HIV screening in the developing world.

Discussion

HIV rapid tests have greatly extended the accessibility of HIV testing by allowing for quick results with minimal equipment and training. Although they perform well in controlled settings, their performance may differ when used on a wide scale in resource-limited settings because of lack of trained staff, poor laboratory infrastructure, and weak quality assurance programs (21). At present, there are at least 3 major limitations to current rapid HIV tests. First, there is decreased accuracy in resource-limited settings. Evaluations of HIV rapid tests in resource-limited settings show decreased accuracy (19, 21), partly because of the difficulty in interpreting weak signals (19). In the US, POC tests for glucose (e.g., Bayer Contour glucose meter) and pregnancy (e.g., Clearblue DIGITAL pregnancy test) have moved toward a digital reading for the user without the need for subjective interpretation (37). The lack of an objective result has led to greater variability between on-site and reference test results, a great concern of quality assurance programs in developing countries, with concordance as low as 82% for HIV-positive samples (21). The second limitation is a reduced diagnostic sensitivity in whole-blood samples and low-titer samples. Whereas current HIV rapid tests are capable of testing various sample matrices, diagnostic sensitivity
is lower in samples with low antibody titers (which could be due to recent seroconversion, autoimmune disorders, or immunodeficiency) and on finger-stick whole blood (20). The third limitation is the potential increase in errors in patient record keeping when performed in resource-limited settings. The lack of automated data transcription and connectivity between POC tests and patient health record systems introduces errors from patient identification; sample labeling and collection; and result recording, retrieval, and formatting (38). In comparison, our mobile device exhibits the high diagnostic sensitivity desired in front-line screening of patients, including detection of weakly positive samples missed by currently recommended HIV rapid tests (Fig. 5), with very few false positives (Figs. 3–5). The 1-touch ease of use and display of an unambiguous result, independent of user interpretation of band intensities, could counteract the observed lower accuracy of rapid tests when practiced in resource-limited settings. The automated wireless synchronization of test results with patient records in the cloud could liberate ELISA-like tests to be performed in truly remote settings with accurate and automated upkeep of centralized patient records (Fig. 4).

This device establishes a proof of concept for how engineering innovations can improve POC healthcare delivery. This study demonstrates how an immunoasay that performs all essential functions of ELISA (chiefly, signal amplification and detection, automated delivery of multiple biochemical reagents, and data processing and communication) can be engineered in a compact mobile device. This goal has been difficult to achieve because of the challenge of integrating individual lab-on-a-chip components into a single functional device (39, 40). Often, components are incompatible with each other; even if integrated, they are not field deployable because of high cost, difficulty of use, or excessive instrumentation (41). The cost of our device is under $1000, compared to over $19,000 for the benchtop equipment needed for conventional ELISA tests in a semiautomated setup (Fig. 1C) (fully automated ELISA setups are even bulkier and more expensive). We note that most of this cost is due to satellite and GSM/GPRS modems (combined cost of $748), which we expect to decrease significantly in time. Moreover, our device, like a cell phone, is inexpensive, easy to use, compact, and easily recharged; the power consumption of our device is similar to that of cell phones (see the online Supplemental Data). Hence, this study demonstrates that a low-cost mobile device can be used for automated, accurate heterogeneous immunoassays on blood samples in resource-constrained regions. Finally, the cost-effectiveness of our microfluidics test, measured by the cost incurred for every disability-adjusted life year saved, is projected to be comparable to vaccinations and oral rehydration therapy (16).

This study also addresses the rapidly emerging area of “mobile health” (12) via an integrated technological approach. For example, recent studies have demonstrated how cell phones can improve patient and public health (42–45), but typically use only off-the-shelf technologies with limited technical features (primarily text messaging). It is likely that mobile health devices with increased functionalities can deliver a highly expanded range of healthcare services right to patients, no matter how remote their location. Access to high-quality laboratory testing is one of the first critical healthcare services needed at the POC in examining each patient. Currently, few handheld POC diagnostics devices have been described, with none having been demonstrated in a compact mobile device or to work with the latest wireless communication technologies. Such a process could also free on-site workers from data entry, reduce the number of errors from manual intervention, and if desired, patient privacy concerns can be addressed by entry of the results into the patient records directly without displaying the results to the health worker. In addition to GSM/GPRS, the device offers a flexible option in access to patient data stored in the cloud via orbiting satellites (Fig. 4, D and E), which offers potential advantages in coverage, scalability, location tracking, cost, and portability (see the online Supplemental Data).

Rather than modifying existing technologies, technologies that bypass a generation of traditional devices could potentially dramatically improve the health of people in low-resource settings. For example, the engineering of cell phones has enabled remote voice communication at a low cost, with the number of users in sub-Saharan Africa rapidly surpassing those using traditional fixed-line communication (46). Although there has been interest in a handheld and mobile-connected rapid blood test, it has been unclear whether such a device can be built to match the performance of ELISA, let alone at sufficiently low cost to make an impact in low-resource settings. This proof-of-concept study establishes the feasibility of this concept by demonstrating that all essential functions of benchtop ELISA, as well as synchronization of patient record data, can be combined into a handheld mobile device that can be operated in a hands-free manner. Such a low-cost mobile device could improve epidemiological surveillance as well as patient care by increasing accuracy to match that of ELISA (for HIV and other biomarkers) and by enabling automatic upkeep and tracking of test results. Before such an impact can be made, additional work would have to be performed, including an expanded evaluation by untrained users, an expanded evaluation of the device’s performance with
early-seroconversion samples (for example, by using a combined antigen/antibody immunoassay as found in recent generations of HIV ELISAs) (34), and integration with live electronic patient records.

Author Contributions: All authors confirmed they have contributed to the intellectual content of this paper and have met the following requirements: (a) significant contributions to the conception and design, acquisition of data, or analysis and interpretation of data; (b) drafting or revising the article for intellectual content; and (c) final approval of the published article.

Authors’ Disclosures or Potential Conflicts of Interest: Upon manuscript submission, all authors completed the author disclosure form. Disclosures and/or potential conflicts of interest:

Employment or Leadership: A.A. Sridhara, Columbia University; D. Steinmiller, OPKO Diagnostics; V. Linder, OPKO Diagnostics.

Consultant or Advisory Role: S.K. Sia, Clars Diagnostics, Inc.

Stock Ownership: D. Steinmiller, OPKO Health, Inc.; V. Linder, OPKO Health, Inc.

Honoraria: None declared.

Research Funding: Columbia University, Coulter Foundation and NIH to Columbia University, Wallace H. Coulter Foundation Phase I and Phase II Career Awards, NIH (SR41NR10753), and Saving Lives at Birth transition grant (United States Agency for International Development, Bill and Melinda Gates Foundation, Government of Norway, Grand Challenges Canada, and the World Bank); C.D. Chin, Frank H. Buck Scholarship.

Expert Testimony: None declared.

Patents: D. Steinmiller, patent number: 8,202,492.

Role of Sponsor: The funding organizations played no role in the design of study, choice of enrolled patients, review and interpretation of data, or preparation or approval of manuscript.

Acknowledgments: We thank Dr. Agnes Binagwaho, Dr. Anita Asimwe, Rwandan Ministry of Health, and Dr. Julius Kamwesiga for facilitating access to clinical samples and for approval of study protocols in Rwanda; Chantal Mutemznaniya for providing clinical samples and reference test results (Muhiina Hospital); Emmanuel Manzi, Eliachim Ishimwe, Carlos Rafael, Kayumba Kizito, and Ernesto Gozzer for access to the TRACNet demonstration site (Voxiva); Veronica Mugisha, David Hoos, and ICAP-Rwanda for facilitating studies in Rwanda; John Kymissis and members of the Sia Laboratory (Columbia University) for helpful discussions; Eric Freitag, Mike Schumman, and Jonathan Cedar for help with prototypes and industrial design of the device (Smart Design); Deborah Johnson and Samuel Cochran for help with industrial design and consultations with Rwandan end users (Pratt Incubator); Enqing Tan for help in assay development and Jason Taylor for help with instrumentation (Clars Diagnostics); Sue Wong (Da-Yeh University), Shing Lee, and Jimmy Duong (Columbia University) for advising on biostatistics.

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Clinical Chemistry 59:4 (2013) 639


