








RESEARCH ARTICLE

Mobile-based and open-source case detection and infectious disease outbreak management systems: a review [version 1; peer review: awaiting peer review]

Alexei Yavlinsky ¹, Swaib A. Lule², Rachel Burns ¹, Alimuddin Zumla³, Timothy D. McHugh ³, Francine Ntoumi^{4,5}, Honorati Masanja⁶, Solomon Mwakasungula ⁶, Ibrahim Abubakar², Robert W. Aldridge ¹

¹Institute of Health Informatics, University College London, London, NW1 2DA, UK

²Institute for Global Health, University College London, London, WC1E 6JB, UK

³Centre for Clinical Microbiology, University College London, London, NW3 2PF, UK

⁴Fondation Congolaise pour la Recherche Médicale, Brazzaville, Congo

⁵Institut für Tropenmedizin, Universitätsklinikum Tübingen, Tübingen, Germany

⁶Ifakara Health Institute, Dar es Salaam, Tanzania

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Abstract

In this paper we perform a rapid review of existing mobile-based, open-source systems for infectious disease outbreak data collection and management. Our inclusion criteria were designed to match the PANDORA-ID-NET consortium's goals for capacity building in sub-Saharan Africa, and to reflect the lessons learned from the 2014–16 West African Ebola outbreak. We found eight candidate systems that satisfy some or most of these criteria, but only one (SORMAS) fulfils all of them. In addition, we outline a number of desirable features that are not currently present in most outbreak management systems.

Keywords

outbreak management, outbreak response, infectious disease surveillance, mobile health, mobile health software, open source, mhealth,

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Any reports and responses or comments on the article can be found at the end of the article.

Corresponding author: Alexei Yavlinsky (a.yavlinsky@ucl.ac.uk)

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Introduction

In an infectious disease outbreak, gathering, sharing and analysing accurate, real-time data about persons with the disease and their contacts is crucial for effective, targeted interventions. This was particularly evident in the 2014–2016 Western Africa Ebola epidemic, during the initial stages of which, poor data management practices significantly contributed to the difficulties in containing the outbreak in Sierra Leone^{1,2}.

The PANDORA-ID-NET consortium³ aims to build capacity for effective outbreak response in sub-Saharan Africa, supported by adequate research and training. As part of this mission, we endeavour to develop a real-time data sharing platform for disease outbreaks that leverages centralised data management and uses mobile technologies for data gathering and feedback. In line with our capacity-building goals, we have committed to accomplishing this using open-source technologies, so that the resulting software packages can be easily deployed on regional IT infrastructure and maintained and further developed by local staff. In addition, this will help ensure that all data collected through an outbreak response system can be stored and processed in the region of origin. The purpose of this paper is to review existing “best practice” open-source systems for outbreak data collection, collation, sharing and analysis, which are used in low- and middle-income settings and could serve as a foundation for the PANDORA-ID-NET consortium data sharing platform.

The rest of the paper is organised as follows. First, to outline what is required from an outbreak management system, we briefly describe the key data-related components of an Ebola outbreak response as identified by the World Health Organization (WHO)⁴. We do so under the assumption that other infectious disease outbreaks will share many essential features with those of Ebola virus disease (EVD)¹. Secondly, to understand the possible challenges in the implementation of these data-related components, and to formulate our inclusion criteria for this review, we summarise the existing academic literature on the shortcomings of data management in the 2014–2016 West Africa Ebola outbreak response. Finally, we identify and review a number of publicly available, mobile-based (usable on a smartphone or tablet), open-source outbreak management systems that satisfy our inclusion criteria. Some of these systems were developed in response to the above EVD outbreak, while the rest were designed in other circumstances. We performed this review by leveraging an existing systematic review by Tom-Aba *et al.*⁵, by conducting our own supplementary rapid literature search and by contacting global experts in field epidemiology.

Key data-related components of outbreak management

The WHO’s Ebola Virus Disease Consolidated Preparedness Checklist⁴ outlines 11 key components of an outbreak response (see [Box 1](#) for the full list). Of these components, *case*

management, surveillance, contact tracing and *laboratory results* require active maintenance and sharing of accurate data amongst outbreak response professionals, and have a high degree of dependence on one another. We give a brief description of each component below.

Box 1. WHO Ebola outbreak management components

- *Coordination* – to enhance national public health emergency preparedness and response plans, and national command and coordination structures, to minimise duplication of efforts and ensure maximum impact from the available resources.
- *Rapid response team* – to be able to act immediately once the first suspected case is reported, irrespective of its geographic location.
- *Public awareness and community engagement* – to harness public trust, counteract false rumours and enhance behaviour to reduce the risk of EVD exposure.
- *Infection prevention and control* – to minimize the risk of transmission of EVD in health-care settings and in the community.
- *Case management* – to strengthen clinical care whilst minimising the risk of transmission to others, including health workers, and to eliminate additional risks such as unsafe burials.
- *Surveillance* – to detect and report any persons with an illness compatible with EVD, or any other unusual health events possibly associated with EVD.
- *Contact tracing* – to identify and follow-up of persons who may have come into contact with an infected person, to stop/limit transmission of EVD to other people.
- *Laboratory results* – to produce rapid confirmations of cases, which is crucial for containing an outbreak, tracing contacts and providing emergency healthcare.
- *Capacities at points of entry* – to prevent cross border transportation of EVD cases by implementing standard operational procedures at international airports, seaports and major land crossings.
- *Budget* – to ensure that both preparedness and response activities are costed in a coordinated and planned manner and sufficient resources are identified to enable their rapid implementation.
- *Logistics* – to ensure that the logistical capacities (such as supply chain management and staffing) required to implement the above components are in place.

Case management

Ebola case management⁶ involves i) suspected case identification (either through routine surveillance or following community-based surveillance alerts), ii) determining whether suspected cases are probable cases by following case definition guidelines, iii) establishing whether probable cases are confirmed cases by obtaining laboratory results, and iv) clinical management of probable and confirmed cases⁷. In ii), the data is recorded using a *case investigation form*, which must be comprehensive and standardised. Additionally, each case must be uniquely linked to the original surveillance alert, the case investigation form data and the subsequent laboratory results. As we describe later, failure to link this data appropriately can lead to case duplication, which in turn affects the accuracy of surveillance data.

¹Note that we exclude systems that deal exclusively with vector-borne outbreaks, as such systems require comprehensive vector control features that are beyond the scope of this review.

Contact tracing

According to the WHO guidelines⁸, all potential contacts of Ebola cases should be identified and closely observed for 21 days from the last day of exposure; contacts that develop illness should be immediately isolated to prevent further transmission of infection. Contact tracing can be broken down into three stages: *contact identification*, *contact listing* and *contact follow-up*.

Contact identification

Contact identification is performed for all cases meeting the EVD case definition, whether alive or deceased. This is done by asking about the activities of the case (the patient) and the activities and roles of the persons around the patient since onset of illness. Persons who lived with or visited the patient since the onset of illness should be identified, as well as the persons, places and healthcare facilities that the patient had visited after they became ill. The contact information collected for each case should be verified for consistency and completeness via repeated interviews conducted during later visits.

Contact listing

At this stage, contact information is entered into the *contact listing form*. The recorded data for each contact should include their name, address, phone number, sex, age, relation to the case, date of last contact with the case, type of contact and whether they are a healthcare worker. This information is used to assess each contact's level of risk of EVD infection, and emphasis is placed on reaching out to high-risk contacts first.

Contact follow-up

Contact follow-up involves monitoring each identified contact daily for 3 weeks, recording whether they develop symptoms indicative of EVD and referring them to hospital if they do (at which point they also become a new case). If a suspected case subsequently tests negative for EVD, their contacts no longer need to be followed up.

Laboratory results

According to the WHO guidelines⁹, all probable and suspected Ebola cases should have their blood specimens collected by trained medical staff at designated healthcare facilities. A number of tests are used to determine the Ebola status of a suspected or probable case, including viral RNA, viral antigen and immunoglobulin M antibody tests.

Surveillance

The EVD consolidated preparedness checklist states that an event-based surveillance system must be in place to “enable timely follow-up of information/rumours from all sources including the community, media, etc.”⁴.

The WHO Ebola contact tracing manual recommends asking people who are being interviewed whether they are aware of any other suspected cases. This is known as “active case finding” and is usually carried out during home visits while performing contact tracing and contact follow-up⁸.

In countries that have had no reported cases of Ebola, alert systems are advised for major land border crossings with

already affected countries and for airports, seaports, and health-care facilities in capital cities. These alert systems should report sick persons who meet the case definition criteria and who have arrived from countries with suspected EVD cases¹⁰.

Challenges in the management of the 2014–2016 Ebola outbreak

During the 2014–2016 West African Ebola outbreak, the government of Sierra Leone suffered considerable setbacks in its attempts to curb the epidemic during its initial stages, which contributed to the persistence of the overall outbreak in the region. Some of these setbacks arose as a result of the country's political challenges and its post-war environment¹. However, problems with data management were also a significant factor^{2,11–13}. Specifically, Owada *et al.* state that inadequate management and integration of multiple data sources meant that at the peak of the outbreak, “reliable epidemiological statistics to determine the actual number of confirmed cases and deaths and to effectively monitor the outbreak could not be obtained”². In the same paper, the authors further highlight individual data management problems that contributed to these inaccuracies:

- *Late arrivals of case investigation forms at district response centres* – as a result, databases were not being updated in time to provide daily summaries and laboratory results had to be used instead for this purpose.
- *Missing variables on case investigation forms and in database entries* – many records did not have information on date of illness onset, sex, age, or residence. Additionally, entries were often inconsistent across multiple databases. These factors limited the ability to measure critical indicators, such as the case fatality rate and incidence rate, and to pursue effective contact tracing.
- *Misclassification of Ebola as other diseases endemic to the region* – one example is malaria, which shares common clinical features with Ebola and may have contributed to delays in recognising some EVD cases. Such confusion was made more likely by missing data such as laboratory results.
- *Difficulties in detecting and merging duplicate case entries* – arising from the use of separate databases for case management and laboratory results, and a lack of database user training.
- *Lack of a consolidated database that captured and linked all data sources in a structured way* – inconsistencies in Excel database formats across different regions complicated national level case data aggregation.

Overall, inaccurate data ingestion and poor data consolidation were the two central data management issues faced during this outbreak by the communicable disease control teams. Therefore, in the next section, we aim to build on these lessons and restrict our review criteria to only include outbreak management software systems that implement all four data components described in our first section in an integrated manner. Furthermore, we choose to focus only on systems that

collect information in real-time via mobile applications running on smartphones and tablets, so as to mitigate the problem of late data arrival highlighted above.

Methods

To identify mobile-based and open sourced outbreak management systems that could meet the challenges that occurred during the management of the 2014–2016 Ebola outbreak, we built upon the systematic review by Tom-Aba *et al.*⁵ that considered systems developed in response to the 2014–2016 West Africa Ebola outbreak. It is reasonable to focus on this outbreak given its scale and impact, and the search strategy employed by the authors is likely to have captured a significant part of development activity in the field of mobile-based outbreak management. However, in the review the authors state that “while it would have been valuable to conduct this review beyond the application of EVD and haemorrhagic fevers and beyond 2015, removing these selection criteria from the search strategy would have resulted in an unmanageably large output with an extremely low positive predictive value”. For this reason, we felt it necessary to carry out our own, supplementary rapid literature review to ensure that we have not missed major developments that occurred after the 2014–2016 epidemic.

This review was conducted by a single reviewer and only considered publications written in the English language. We used Google Scholar as the primary tool for our literature searches. Our preliminary inclusion criteria were “*outbreak management systems that include at least two of the four key data components described in the ‘key data-related components of outbreak management’ section and have a mobile component*”. Note that these are not specific to EVD and are less stringent than our ultimate inclusion criteria that necessitate all four data management components being present. The preliminary criteria act as a filter to increase the positive predictive value of the candidate outbreak management systems without significantly reducing the sensitivity of the search results.

Table 2 shows the search queries we used to create a pool of candidate publications. Note that this involves searching for all pairwise combinations of keywords corresponding to the

key data components. Additionally, we used the keywords “*outbreak*” and “*android*”. We settled on the latter as a catch-all term for “mobile applications”, since the latest data shows that Android has a market share of 83.1% in all of Africa¹⁴. We also carried out a PubMed search using the following MeSH query:

```
((((Software[mh:noexp]) OR Mobile Applications
[mh:noexp]) OR Cell Phone[mh]) OR
Telemedicine[mh:noexp]) AND ((Disease Outbreaks[mh])
AND Epidemiologic Methods[mh]).
```

To increase the coverage of our review further, we contacted international experts that participated in the second International Conference on Reemerging Infectious Diseases (ICREID). The conference took place in March 2019 in Addis Ababa, Ethiopia. Conference organisers contacted every participant via email and asked them to tell us about outbreak management systems they had used.

Results

Table 3 summarises the results of our literature search, executed in February 2019.

The Google Scholar search strategy yielded 1016 unique publications; only nine described systems satisfying the preliminary criteria, of which six were not listed in the systematic review by Tom-Aba *et al.*^{5,15–20}. The PubMed search returned 231 results but did not increase the number of publications matching the above criteria. Via personal communication with expert field epidemiologists, we were informed of three commercial and proprietary outbreak management systems^{21–23}. Finally of 475 ICREID 2019 conference attendees, 38 told us about their experiences and indicated that they had taken part in at least one outbreak investigation. In total, 16 reported using an electronic outbreak management system, and three additional systems were discovered this way^{24–26}.

The combined search strategy detailed above yielded 1022 unique citations, of which 1007 were excluded, and 15 were retrieved. A PRISMA flow chart providing a visual summary of our screening process can be found in Figure 1.

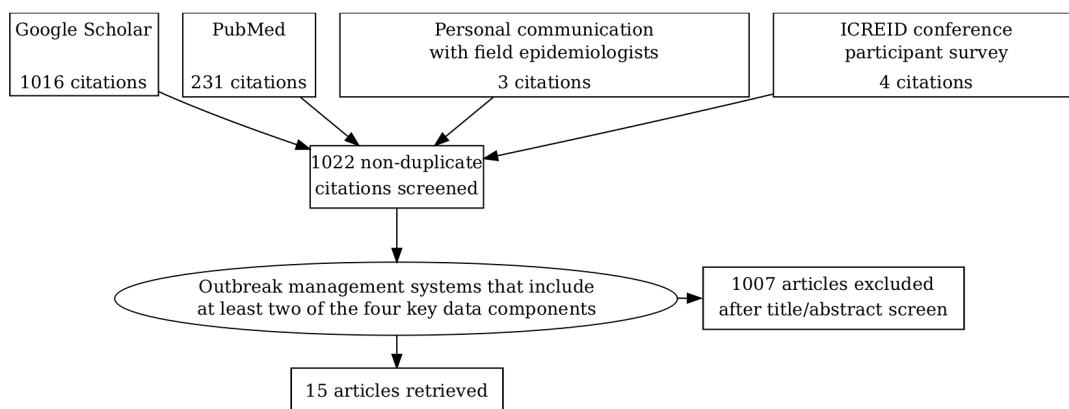


Figure 1. The PRISMA flowchart of our rapid review screening process.

Amongst the 58 identified systems related to EVD management in 2014 and 2015 identified by Tom-Aba *et al.*⁵ and shown in [Box 2](#), only three appear to contain all four key data management

Box 2. List of the 58 systems identified in the systematic review by Tom-Aba *et al.*⁵

BioCaster Portal, Bio-Sense 2.0, BSVE, CDRs Simulator, Cell phone messaging technology, CKAN, CliniPAK, Collaborative Overarching Multi-feed Biosurveillance System (COMBS), CommCare Contact Tracing, Data De-Identification Toolkit, DHIS 2, Doctor App, Early Warning systems (EWS), Sense Ebola Followup, Ebola Spatial Care Path (POCT), Ebola Tracks, EbolaAlert, EIDSS, EpiRobot, Esoko SMS app/WhatsApp, ESSENCE-FL, Facebook, Flu Caster, Google Analytics, GPHIN, GSMS, Hadoop, Health 2.0, Healthmap, HIT, iPhone app, LEEDS, mHealth real-time infectious disease interface (contact tracing app), NNDSS, Open Data Kit, OpenESSENCE, OpenMRS, OpenStreetMap (maapJack), PHIN-MS, Polly, POP (Practice-Oriented Project) on Crowdmap, QGIS, R, RapidSMS, Response Call Center app, SAGES, Screening expert system (SES), Sentinel surveillance system (SSS), SMARTech, Smartphone-based contact tracing system, SORMAS, SoundCloud, SWAP (surveillance window app), Telefónica, Telemedicine, The Minnesota African Task Force Against Ebola (MATFAE), Twitter, WBDS

components (case management, surveillance, contact tracing and laboratory results). These systems are SORMAS²⁷, CommCare Ebola Response²⁸ and the Sense Ebola app²⁹. We give our description of these systems below and then list five additional systems that also have all of these components. We found these systems amongst the 15 citations we retrieved using our search strategy, which we described in the previous section. The combined summary of these eight systems can be found in [Table 1](#).

Surveillance and Outbreak Response Management and Analysis System (SORMAS)

SORMAS is an open source system for case management, contact tracing, surveillance, and laboratory sample management^{27,30}. Data is collected using mobile devices running the Android operating system and data aggregation and analysis are performed in real-time via a web application interface powered by software running on a remote server. While the original 2015 implementation of this web application relied on the commercially licensed SAP database²⁷, the 2017 edition replaced the latter with PostgreSQL, thus making the overall system completely open-sourced^{31,32}. The 2015 version was designed exclusively for EVD surveillance and management,

Table 1. Comparison of the eight identified outbreak management systems meeting all four key data management criteria. Note that none of the above systems offer clinical trial data management. *Planned feature.

Systems	Surveillance	Case mgmt.	Contact tracing	Lab results	Open source	One health	Passive data	Training materials	Multiple diseases
SORMAS	✓	✓	✓	✓	✓			✓	✓
CommCare Ebola	✓	✓	✓	✓			✓		
Sense Ebola Followup	✓	✓	✓	✓					
AfyaData	✓	✓	*	*	✓	✓			✓
HPZone	✓	✓	✓	✓					✓
EpiInfo	✓	✓	✓	✓					✓
Conduent Maven	✓	✓	✓	✓					✓
Atlas WorldCare	✓	✓	✓	✓					✓

Table 2. Google scholar queries for the rapid review of additional systems not identified in Tom-Aba *et al.*⁴. There were 1016 unique publications after pooling all query results.

Query	Results
("contact tracing" OR "contact tracking") "surveillance" "android" "outbreak"	60
("contact tracing" OR "contact tracking") "case management" "android" "outbreak"	22
("contact tracing" OR "contact tracking") "laboratory" "android" "outbreak"	51
"surveillance" "case management" "android" "outbreak"	86
"surveillance" "laboratory" "android" "outbreak"	960
"case management" "laboratory" "android" "outbreak"	71

Table 3. Outbreak management systems with at least two key data components.

Systems	Surveillance	Contact tracing	Case mgmt.	Lab results
Systems identified in Tom-Aba et al.⁵				
BioCaster Portal	✓	?	✓	
Bio-Sense 2.0	✓	?	✓	
Collaborative Overarching Multi-feed Biosurveillance	✓	?	✓	
CommCare Contact Tracing	✓	✓	✓	✓
Sense Ebola Followup	✓	✓	✓	✓
Ebola Tracks	✓	✓		
mHealth real-time infectious disease interface	✓	✓		?
NNDSS	✓	?	✓	
Open Data Kit	✓	✓		
Sentinel surveillance system (SSS)	✓	?	✓	
“Smartphone-based contact tracing system”	✓	✓		
SORMAS	✓	✓	✓	✓
“Telemedicine”	✓		✓	
Systems identified through our rapid review strategy				
AfyaData	✓		✓	
HPZone	✓	✓	✓	✓
Conduent Maven	✓	✓	✓	✓
Atlas WorldCare	✓	✓	✓	✓
EbolaDiag ¹⁶		✓	✓	
Coconut Plus ¹⁷	✓	✓	✓	
Ebola telemonitoring system ¹⁸	✓			✓
Smartphone-based molecular diagnostics system ¹⁹	✓			✓
OpenMRS-Ebola EHR ²⁰			✓	✓

in partnership with the field workers and epidemiologists at the Ebola Emergency Operations Centre in Nigeria, building on the latter’s experience of successfully containing the country’s Ebola outbreak that was concomitant with the West African epidemic²⁷. The authors identified different “personas”, or user roles, involved in the process of EVD outbreak management (e.g. informants, rumour officers, surveillance/case/contact officers and supervisors). For each role, the authors established the relevant activities, information items and interactions with other roles, and used these to define the information flow between the different user types. To give one example, “*a rumour officer conducts an initial triage on all incoming rumours concerning possible cases, and uses the rumour information checklist to report the results of this triage to the surveillance supervisor*”. SORMAS was then designed to facilitate and capture this information flow via the corresponding system modules. One reportedly unique feature of this design was that the flow of information was bi-directional, such that supervisors

could instruct officers on the follow-up steps that needed to be taken²⁷.

The latest (2018) update of the system incorporates epidemiological data capture, outbreak management user roles and information flows for several additional diseases, such as Lassa fever, monkeypox, bird flu, dengue, yellow fever, measles, meningococcal infections, *Yersinia pestis* and cholera³³. Data aggregation and analysis are implemented as a web-based multi-user overview dashboard. It includes live case data, epidemiological curves, case maps displayed via an embedded GIS visualisation module and transmission chain network diagrams constructed from contact tracing data (see [Figure 2–Figure 5](#), taken from [33](#)). These features were implemented as a result of several “design thinking” focus group workshops with Nigerian target users, carried out in Nigeria and Germany between 2015 and 2017^{33,34}. As of 2018, the Nigerian Centre for Disease Control recommends that health

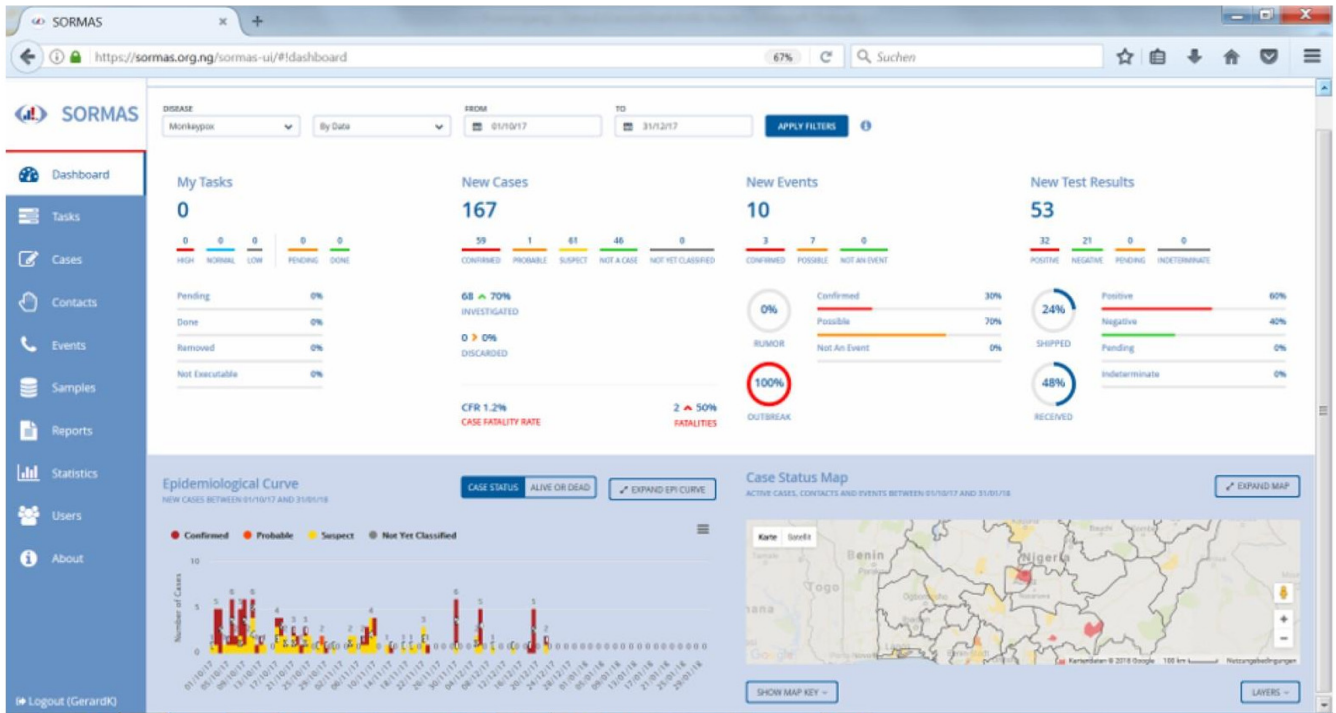


Figure 2. National level dashboard of SORMAS: monkeypox, December 2017.

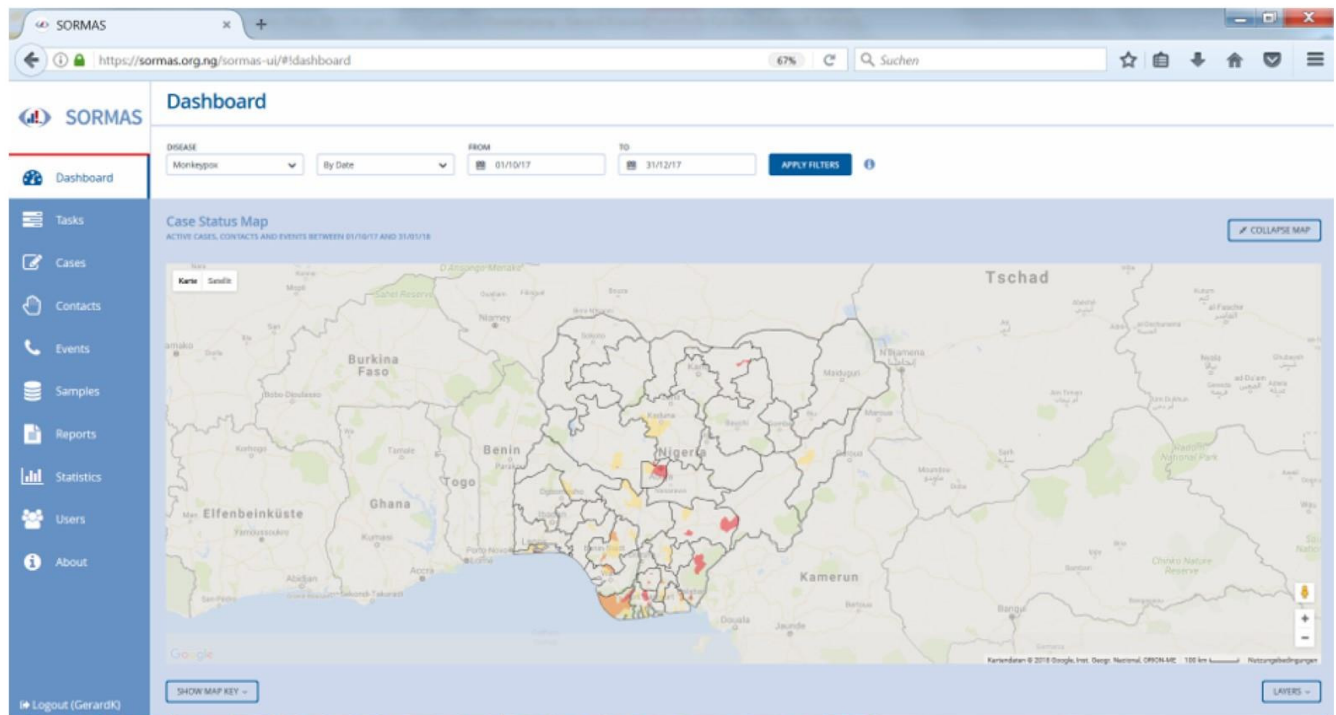


Figure 3. National level dashboard of SORMAS: monkeypox, cumulative incidence by Local Government Authority, December 2017.

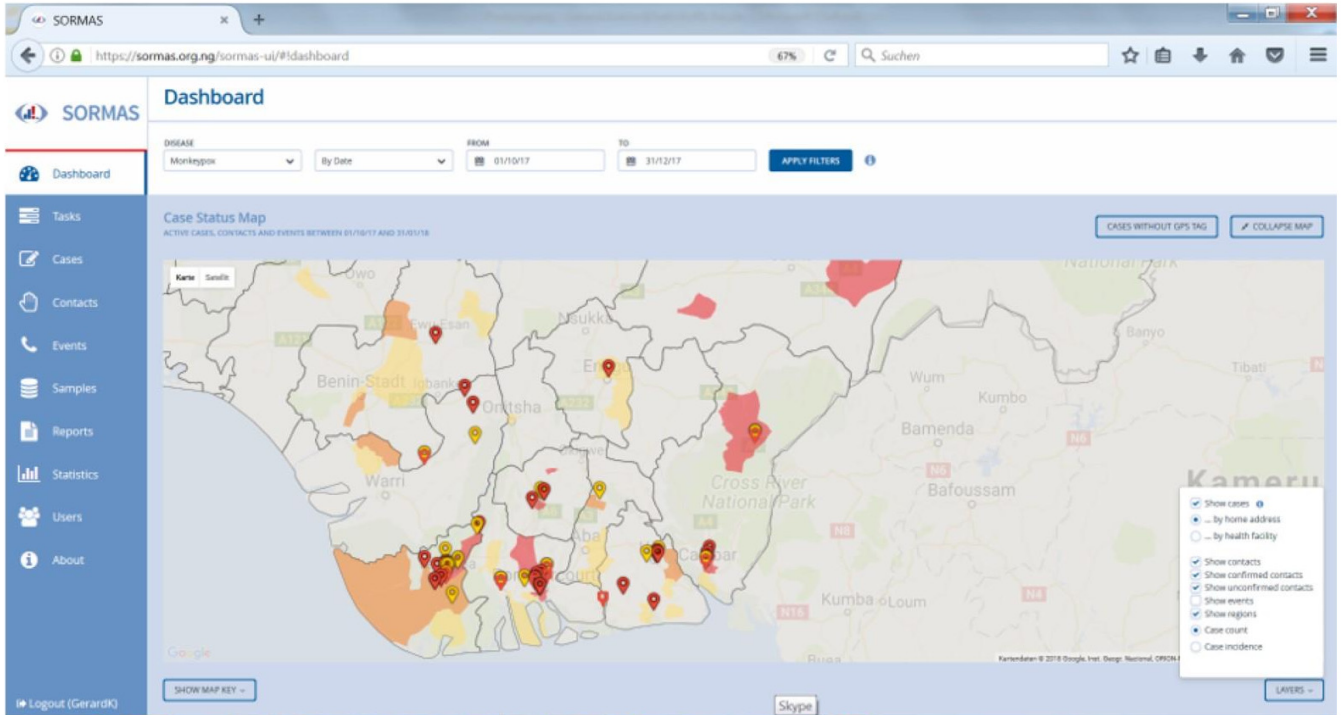


Figure 4. National-level dashboard of SORMAS: monkeypox, GIS-location of cases (red) and contacts (yellow), December 2017.

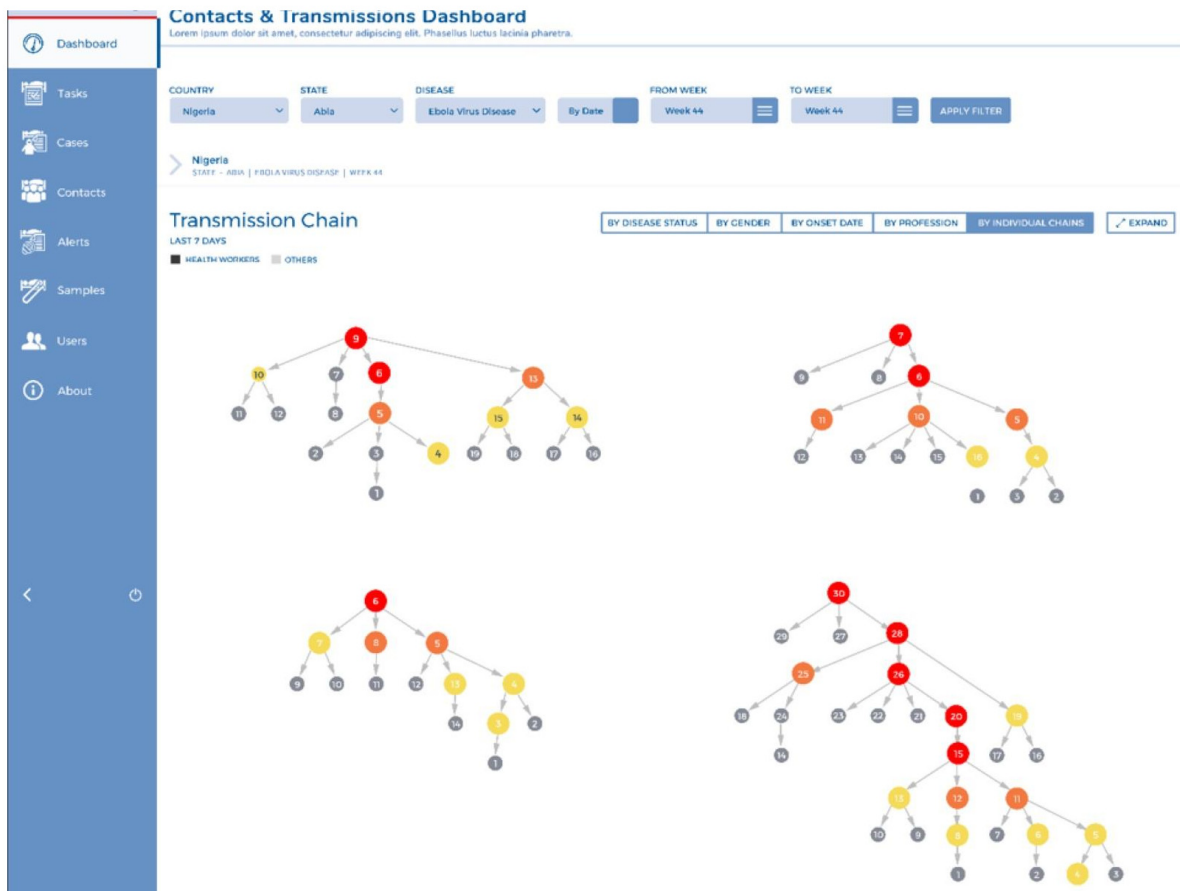


Figure 5. SORMAS: contacts and transmission chain dashboard.

facilities and local governments across all of the country's 36 states deploy SORMAS³⁵. An online demo of the SORMAS dashboard is publicly available³⁶.

CommCare Ebola Response

CommCare is a cloud-based software development platform that enables users to design open source mobile applications for data collection and to distribute these applications to Java-based and high-end Android phones, with the collected data being sent back to the CommCare HQ data analysis portal³⁷. A special EVD management system was set-up using this platform, comprising of case management, surveillance, contact tracing and laboratory result tracking, but with the caveat that the gathered data is hosted at CommCare²⁸. As a result, this platform does not satisfy our capacity-building requirement of enabling affected countries to host the outbreak management system entirely on local IT infrastructure. Additionally, while the system has been built using open-source technologies, its source code is not available for public download. This means that it cannot be enhanced independently of the original vendor, which further invalidates the use of CommCare Ebola Response under our criteria.

Sense Ebola Follow-up

Sense Ebola Follow-up was originally an Android-based, real-time data capture mobile application that guided health workers through the process of registering a contact and performing a follow-up. It was developed at the peak of the West African Ebola outbreak in 2014. Since then it has been extended to work with both Android and iOS devices, and provides case investigation, contact listing and contact follow-up forms, as well as functionality to make a laboratory investigation request. A server-side data integration and analysis dashboard is also provided^{15,29}. However, as with CommCare Ebola Response, the source code is not available for public download, which makes Sense Ebola Follow-up unsuitable for capacity building purposes.

AfyaData

AfyaData is an open-source infectious disease surveillance system developed at the Southern African Centre for Infectious Disease Surveillance (SACIDS) in Tanzania¹⁵. It consists of an Android-based mobile application and a web-based application acting as a server. The mobile app is used for collecting and submitting surveillance data, and for receiving and tracking feedback while the server component is responsible for data storage and management. The following activities are supported by the system: *community-based participatory disease surveillance* (for timely detection and reporting of disease events at the community level), *official surveillance strategy* (for timely collection and submission of disease data at the health facility level) and *two-way communication feedback* to individuals who report disease events at community and health facility levels. Notably, contact tracing and laboratory result management are absent from the set of features listed by Karimuribo *et al.*¹⁵. Despite this, we have included AfyaData as an exception because development work on this system is ongoing³⁸. The system has been trialled during the latest Ebola outbreak in the Democratic Republic of Congo³⁹, where it was used for syndromic surveillance.

Commercial and proprietary systems

During the 2014–2016 West African Ebola outbreak, eleven people were treated for EVD in the United States⁴⁰. This created a risk of an EVD outbreak in the country and two commercial software vendors responded to this threat by offering outbreak management tools with specific Ebola-related features. Maven by Conduent²¹ and WorldCare by Atlas Software^{22,41} both purportedly provide case management, surveillance, contact tracing and laboratory result management functionalities. However, no public documentation is available for these systems (one has to request a private demo to see how they operate) and there is currently no prospect of either Maven or WorldCare becoming free of charge and open source.

HPZone is Public Health England's disease surveillance and outbreak management system²³. It provides case management, surveillance, contact tracing and laboratory result management for up to 100 different diseases but is neither publicly available nor open source.

Our emails to participants at ICREID identified four additional systems: EpiInfo²⁴ (used by four participants), Open Data Kit²⁵, HPZone²³ and KoBoCollect²⁶ (each used by one participant). The other eight respondents did not provide the names of the systems they used, and one participant reported using an Excel spreadsheet. In total, six respondents used their outbreak management system on a tablet or a smartphone. Of the named systems, EpiInfo, KoBoCollect and HPZone were reported to have all four key data components of outbreak management. However, EpiInfo is a desktop-based application and neither it nor HPZone are open source. Meanwhile, KoBoCollect is similar to Open Data Kit, in that it is a mobile-based data collection platform that requires users to design their own data entry forms instead of having built-in outbreak management functionality. As a result, none of the systems mentioned by the survey respondents satisfy our inclusion criteria.

Discussion

Our review found numerous existing mobile-based outbreak management systems, but only SORMAS satisfies the capacity-building requirements of PANDORA-ID-NET (open source code and the ability to store gathered data in the region of origin) and fully integrates data from case management, contact tracing, laboratory work and surveillance components, in line with the lessons learned during the 2014–16 West African Ebola outbreak.

The PANDORA-ID-NET consortium aims to take a multi-faceted approach to building outbreak response capacity. In addition to standard preparedness measures, this includes strengthening the surveillance of zoonotic diseases, improving the quality of collected syndromic and laboratory data and facilitating clinical trials of relevant interventions. We describe below the corresponding features that would be complementary to the four key data components of an integrated outbreak management system and outline why these features are desirable.

Zoonotic disease surveillance

Many infectious disease outbreaks are due to emerging infectious diseases (EIDs). The latter are defined as infections

that have appeared in a population for the first time or have previously been present but are rapidly increasing in incidence or geographic range⁴². It is estimated that approximately 60% of such diseases have zoonotic origins and 72% of these have originated in wildlife⁴³. Surveillance and management of zoonotic EIDs has multiple components:

- *Domestic and livestock disease control*. This requires animal vaccination, vector control, test and treat, cull and quarantine programs, as well as the participation of local populations in animal disease surveillance and reporting⁴⁴.
- *Wildlife disease control*. This is achieved through regular examinations of animals in the wild for signs of disease using macroscopic, histopathological, bacteriological and parasitological analyses⁴⁵.
- *Ecological surveillance*. There is mounting evidence that human-led ecological disruption is contributing to emerging (and re-emerging) zoonotic diseases⁴⁶. It has been hypothesised that changes in land use in the Guinea Forest Region, such as intensified agriculture and clear-cut logging, played a significant part in the ecotypic shift of the Ebola virus before the 2014–2016 West Africa outbreak. This shift turned a self-limiting rural infection into a proto-pandemic disease, capable of spreading to densely populated urban areas⁴⁷. The goal of ecological surveillance is to monitor the environment for changes, e.g. in land use or wildlife population levels, and establish how these changes alter the risk of zoonotic infection re-emergence. One example of this type of surveillance is predicting the spread of zoonotic monkey malaria infection in areas with sparse incidence data, using deforestation patterns and other environmental information⁴⁸.

The domestic, livestock and wild animal disease control components are collectively referred to as “one health” in the context of epidemiological surveillance. Out of the systems we identified, only *AfyaData* offers animal disease surveillance features¹⁵ and none have ecological surveillance capabilities.

Passive data collection

There has been recent progress in rapid Ebola testing using mobile and point-of-care devices^{18,49}. Outbreak management systems would benefit from automatically collecting data from such devices to increase the data collection speed and reduce data entry errors. Of the reviewed systems, only CommCare Ebola offers such functionality²⁸.

Clinical trial data management

At the peak of the 2014–2016 Ebola epidemic, the WHO convened a panel to discuss the ethical permissibility of using unregistered treatments during such outbreaks⁵⁰. It concluded that “it would be acceptable on both ethical and evidential grounds to use as potential treatments or for prevention unregistered interventions that have shown promising results

in the laboratory and in animal models but have not yet been evaluated for safety and efficacy in humans, provided that certain conditions are met.” However, this recommendation came with the caveat that “researchers have a moral duty to evaluate these interventions (for treatment or prevention) in clinical trials that are of the best possible design in the current exceptional circumstances of the West African Ebola outbreak, in order to establish the safety and efficacy of the interventions or to provide evidence to stop their use. Continuous evaluation should guide future interventions.” In light of these recommendations, clinical trial data management will become essential in future outbreak management scenarios. However, none of the reviewed systems support this functionality.

To summarise the above, zoonotic disease surveillance, passive data collection and clinical trial data management – features that are important for strengthening outbreak response preparedness – are not currently present in most of these systems, including SORMAS.

Our review of systems was rapid, since it was conducted by a single reviewer and only considered publications written in the English language. Additionally, the grey literature search scope was limited. However, this review was also rigorous, as we leveraged the results of an existing systematic review of this field by Tom-Aba *et al.*⁵, conducted our own supplementary review to increase coverage, and contacted experts working in this area to identify systems they have used that were not published in the academic or grey literature that we searched. Although the scope of Tom-Aba *et al.*'s review is limited to the 2014–16 Ebola outbreak, our broader supplementary search did not uncover additional systems that satisfy our own inclusion criteria. As a result, we believe that our review comprehensively covers the field of mobile-based outbreak management systems (apart from those that deal exclusively with vector-borne diseases). However, this is notwithstanding the fact that there are proprietary systems for internal use without sufficient public exposure that we could not include in this review. Humanitarian agencies may have their own in-house systems for outbreak management without any associated publications. One example is Médecins Sans Frontières' Health Surveillance Programme (HSP)⁵¹, which uses mobile devices in conjunction with the commercially licensed Dharma software platform for data collection and management via a dashboard interface⁵². In 2015, HSP was deployed in Najaf Governorate, Iraq for real-time identification of scabies outbreaks. Although MSF report significant data collection speed improvements and cost savings, very little information is available on the actual functionality of this system.

Systematic evaluation of outbreak management system performance remains an outstanding research question. SORMAS boasts a formidable level of functionality³³, has an impressive regional deployment coverage³⁵ and has been subjected to several field-user evaluation exercises that have returned satisfactory results³¹. However, disease outbreaks are unforeseen events by

their nature, making it challenging to design a consistent set of evaluation criteria for objectively rating and comparing how successful these systems are in reducing the numbers of new cases in an ongoing epidemic.

The implication of our review is that SORMAS is a mature system that is ready to be disseminated and rolled out in regions with high infectious disease burden, and, owing to the system's open-source design, can be further adapted to meet specific public health needs of individual countries. Future areas of research and development for SORMAS could include zoonotic disease surveillance, passive data collection and clinical trial data management. A thorough systematic review for each of these areas would help to establish the existing best practice and the appropriate scope of the necessary development work.

Conclusion

Mobile-based digital outbreak management is an emerging field, with new tools being continuously developed. Out of the identified outbreak management systems, only SORMAS satisfies all of the inclusion criteria. Additionally, we have outlined a number of desirable features that are not currently present in most outbreak management systems, including SORMAS. Our paper provides a timely review of the state of the art mobile-based and open source case detection and infectious disease outbreak management systems that we hope others can use as a source for identifying tools for their research and communicable disease control efforts.

Data availability

All data underlying the results are available as part of the article and no additional source data are required.

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