Automated and partially-automated contact tracing: a rapid systematic review to inform the control of COVID-19

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Abstract

Background

Automated or partially-automated contact tracing tools are being deployed by many countries to contain SARS-CoV-2; however, the evidence base for their
use is not well-established.

Methods

We undertook a rapid systematic review of automated or partially-automated contact tracing, registered with PROSPERO (CRD42020179822). We searched PubMed, EMBASE, OVID Global Health, EBSCO COVID Portal, Cochrane Library, medRxiv, bioRxiv, arXiv and Google Advanced for articles relevant to COVID-19, SARS, MERS, influenza or Ebola from 1/1/2000-14/4/2020. Two authors reviewed all full-text manuscripts. One reviewer extracted data using a pre-piloted form; a second independently verified extracted data. Primary outcomes were the number or proportion of contacts (and/or subsequent cases) identified; secondary outcomes were indicators of outbreak control, app/tool uptake, resource use, cost-effectiveness and lessons learnt. The Effective Public Health Practice Project tool or CHEERS checklist were used in quality assessment.

Findings

4,033 citations were identified and 15 were included. No empirical evidence of automated contact tracing’s effectiveness (regarding contacts identified or transmission reduction) was identified. Four of seven included modelling studies suggested that controlling COVID-19 requires high population uptake of automated contact-tracing apps (estimates from 56% to 95%), typically alongside other control measures. Studies of partially-automated contact tracing generally reported more complete contact identification and follow-up, and greater intervention timeliness (0.5-5 hours faster), than previous systems. No meta-analyses were possible.

Interpretation

Automated contact tracing has potential to reduce transmission with sufficient
population uptake and usage. However, there is an urgent need for well-designed prospective evaluations as no studies provided empirical evidence of its effectiveness.
Introduction

In response to the rapid global spread of SARS-CoV-2 since December 2019, governments worldwide have applied widespread social distancing measures to attempt to curb transmission\(^1\). These policies have suppressed case numbers\(^2,3\) but have substantial economic, social and indirect health consequences,\(^4\) leading to a growing focus on alternative control strategies.\(^5\)

Contact tracing is a well-established part of infectious disease outbreak management which aims to interrupt chains of infection transmission (for example, through quarantining contacts) and has formed part of many countries’ initial or ongoing response to the COVID-19 pandemic.\(^6,7\) Traditionally, contact tracing involves a case recalling their recent contacts, who are subsequently contacted and given public health advice to limit onward transmission. A contact tracing system’s ability to reduce disease transmission depends on how rapidly and comprehensively it can identify and (if applicable) quarantine contacts relative to infectious period,\(^8–10\) and on quarantine adherence.

Typically, contact tracing’s limitations include incomplete recall of contact events by cases, the time taken to notify contacts manually, which can delay quarantine,\(^11\) and the fact that it is often resource-intensive and time-consuming.\(^8,9\) Technology could address some of these limitations, including by automating processing of test results or symptom reports\(^12\) and using smartphones’ capabilities (e.g. Bluetooth) to identify and notify at-risk contacts instantaneously.\(^11,13\) Automated contact tracing for COVID-19 has been deployed in several countries\(^14,15\) and is commencing in the UK.\(^16\) However, the practical, legal and ethical considerations involved are complex\(^16–18\) and take-up, privacy, security, and testing access have been identified as potential barriers to effectiveness.\(^17,19\)

This rapid systematic review aims to assess the effectiveness of automated and partially-automated contact tracing systems in identifying at-risk contacts and in controlling disease transmission in humans, to inform discussions about
the balance between benefits and potential risks of automated contact tracing in controlling COVID-19.

Methods

This rapid systematic review is registered with PROSPERO (CRD42020179822) and our protocol is available as a pre-print.20

Search strategy and selection criteria

We searched PubMed, EMBASE, and OVID Global Health for articles from any setting published between 1 January 2000 to 14 April 2020. We supplemented this with searches of medRxiv, bioRxiv arXiv, EBSCO Medical COVID Information portal, Cochrane Library and Google Advanced (see Supplementary Information for search terms), and scanned relevant references of included studies. We also included studies identified through professional networks up to 30 April 2020.

Primary outcomes of interest were the number or proportion of contacts identified and the number or proportion of contacts who go on to become cases that are identified (‘contacts’ referring to those considered at-risk due to their exposure to a case). Secondary outcomes included were: impact on either R₀ or Rₑ (basic or effective reproduction number; the average number of secondary cases infected by one infectious person, in a completely susceptible or real-world population respectively) or other indicators of outbreak control (e.g. completeness or timeliness of contact follow-up or intervention); population uptake (i.e. app uptake or participation); resource requirements (e.g. time, financial resources, testing capacity, training or specific expertise) or cost-effectiveness (e.g. cost per case prevented or per quality-adjusted life year); ethical considerations and lessons learnt from implementation of an automated or semi-automated contact tracing system.

Our original protocol included data security, privacy issues and public perception but was modified to exclude these outcomes, partly because they are addressed by the Ada Lovelace Institute report17 which was published
during our review process, and to focus on evidence of effectiveness from a public health perspective.

We included interventional, observational, modelling and case studies related to automated or partially-automated contact tracing in humans that reported findings regarding at least one outcome of interest. We included studies of COVID-19, SARS, MERS, influenza, or Ebola or, in modelling studies, hypothetical infections spread through respiratory transmission. Studies in which some contact tracing processes were automated (e.g. automated calculation/updating of follow-up periods, contact list generation, alert generation, transmission mapping) but which did not use data from a device as a proxy for contact, or which required users to notify contacts, were considered partially-automated. Purely qualitative study designs were excluded, as were app protocols and studies of monitoring during quarantine. Articles with or without comparators were considered eligible. Both pre-print and peer-reviewed articles were included.

Our search was restricted to full-text manuscripts in English. Non-English language studies flagged for full text review have been collated in supplementary information (table S6). Title and abstract screening was performed by two researchers [IB and TC], with 10% of excluded records dual screened. Full-text screening for eligibility was undertaken by two reviewers [IB and MB/TC]. Discrepancies were resolved by consensus, with an independent view given by a third reviewer [TC or RA]. All exclusion decisions were documented.

Data analysis

One reviewer [IB] extracted data (see protocol for details)\textsuperscript{22} using a standardised, pilot-tested spreadsheet. Data extraction was reviewed for each study by a second reviewer [MB or TC]. One reviewer quality appraised studies [IB], using the Effective Public Health Practice Project tool for interventional/observational study designs\textsuperscript{21} or using an adapted version of the CHEERS checklist\textsuperscript{22} for modelling studies. In the absence of an appropriate standardised tool for appraisal of descriptive case studies, we documented key factors likely to influence study quality (selection or information bias,
confounding, selective reporting, conflicts of interest). We synthesised study findings narratively. We specified in the protocol\(^{20}\) that meta-analyses would be considered for \(\geq 3\) papers investigating a comparable intervention within a similar disease context with a comparable quantitative primary outcome.

**Role of the funding source**

There was no specific funding for this project. IB and TC are National Institute for Health Research Academic Clinical Fellows. RWA is supported by a Wellcome Trust Career Development Fellowship [206602].

**Results**

We identified 4,033 records from database searches, 398 of which were excluded as duplicates and 110 were reviewed as full text (see PRISMA flowchart in figure 1 for details); two further relevant studies were identified through professional networks and one from reference lists of included studies. 15 records were included and had data extracted. Extracted data are summarised in tables 1-2, which respectively detail key study characteristics including populations, interventions and comparators (table 1) and outcomes and key findings (table 2). Supplementary table S1 details modelling studies’ key assumptions and input parameters and supplementary table S2 details findings and lessons learnt further. We did not undertake any meta-analyses as our pre-specified criteria for this were not met.

Included studies’ findings are detailed below in three categories, the third of which was defined post-hoc: (1) seven studies that addressed automated contact tracing directly (all modelling studies focused on COVID-19)\(^{11,23-28}\), (2) five descriptive observational or case studies of partially-automated contact tracing (four studies related to Ebola\(^{29-32}\) and one hospital infection control system)\(^{33}\), and (3) three studies of automated contact detection within a relevant disease context but without subsequent tracing or contact.
No study assessed ethical considerations relevant to decision-making were discussed by two studies (see table 2 for details).\textsuperscript{11,29}

1. Studies of automated contact tracing

We found seven studies of automated contact tracing; all were mathematical modelling studies, with varied assumptions (supplementary table S1). Five of these addressed smartphone apps\textsuperscript{11,23-26} specifically, alongside other wearable devices in one study.\textsuperscript{25} Two studies related to an unspecified type of device carried by users.\textsuperscript{29,30} No studies contained data on our primary outcomes using the same definition used in our protocol (number or proportion of contacts (and of contacts that go on to become cases) identified); however, two of the seven modelling studies provided data of a comparable and relevant nature in the form of estimated numbers of contacts quarantined.

In a modelling study of control measures for COVID-19 in the UK, Kucharski and colleagues\textsuperscript{23} estimate that a median of four contacts per case (mean 14) would be quarantined under automated contact-tracing, compared to 28 (mean 39) with all contacts traced manually, assuming 90\% adherence to quarantine. Also modelling COVID-19 in the UK, Hinch and colleagues\textsuperscript{24} assumed 100\% initial adherence to quarantine and 80\% uptake amongst smartphone owners, and estimated that approximately 10-15 million people would be quarantined (cumulatively, at any given time, alongside the over 70 ‘shielding’ population), but did not present numbers of contacts identified per case. Three studies described an approximately quadratic relationship between population uptake of an automated contact tracing tool/app and associated reductions in transmission,\textsuperscript{27,28,23} such that 80\% uptake might enable notification of approximately 64\% of the contacts who would be notified in an optimal contact tracing system; with 50\% uptake the corresponding figure is 25\%.\textsuperscript{28}

Only Kucharski and colleagues\textsuperscript{23} directly compared automated and manual contact tracing’s modelled impacts on $R_0$ or $R_c$. Under ‘optimistic’ assumptions including 75\% uptake amongst smartphone owners (see supplementary table S1), and assuming equal maximum delays to quarantine of contacts under automated and manual scenarios, they estimated that automated tracing
alone reduced $R_e$ by 44% whereas manual tracing of all contacts reduced it by 61%. Hinch and colleagues\textsuperscript{24} did not compare automated and manual contact tracing or report impacts on $R_e$. Both studies\textsuperscript{23,24} found that suppressing the COVID-19 outbreak required concurrent measures (e.g. shielding vulnerable groups,\textsuperscript{24} remote working and limits on numbers of contacts per day\textsuperscript{23}) alongside automated contact tracing. Most scenarios modelled by Hinch and colleagues\textsuperscript{24} did not achieve containment (equivalent to $R_e<1$), except when quarantining all household members of contacts who had direct contact with a case.\textsuperscript{24}

Two other modelling studies of automated contact tracing for COVID-19 reported similar findings: one study\textsuperscript{27} estimated 75\%–95\%, and another 90–95\%,\textsuperscript{25} population-wide uptake to be required to bring $R_e$ below 1. Several studies found that, even below this threshold, increasing uptake was associated with reduced COVID-19 incidence.\textsuperscript{27,24,26}

Regarding resource requirements, one study\textsuperscript{26} estimated that approximately 200,000 tests/day would be required for test-based quarantine release in the UK; another\textsuperscript{23} estimated 30–50 tests required per case detected. No other secondary outcome data were reported for this section.

2. Studies of partially-automated contact tracing

We found a total of five studies of partially-automated contact tracing, which all automated some processes within systems involving human contact tracers or infection control staff. Li and colleagues\textsuperscript{33} profiled a hospital-based system which automatically alerts staff to new infections by target organisms and generates contact lists using user-defined parameters (e.g. having shared a room, concurrent contact, duration of contact). Four studies\textsuperscript{29–32} focused on software applications used to manage Ebola outbreaks.

Three of these studies reported data relevant to our primary outcomes; in one\textsuperscript{32} a mean of 36 contacts per Ebola case were recorded for cases where contact tracers used an app (‘Ebola Contact Tracing application’), compared with 16 per case under the pre-existing paper- and Excel-based system. In a second\textsuperscript{30} study >100,000 investigated cases and >50,000 contacts were
recorded in the Epi Info Viral Hemorrhagic Fever (VHF) application by contact tracers across 7 African countries and 2 US states by end 2015; the reason for this apparent low ratio of only approximately 0·5 contact per case recorded was unclear. A third study of the CommCare app, a partially-automated application with algorithm-based decision-support features (e.g. prompting referral for testing on entry of data indicating that a contact developed symptoms) and which updated a data visualisation dashboard automatically every hour, reported 9,162 contacts but the number of cases of these contacts was unspecified. No other primary outcomes were reported in these studies.

Contact follow-up rates were increased compared with previous paper-based systems in two studies in this section. Two studies reported improved intervention timeliness (e.g. quarantine or isolation) compared with previous, non-automated systems; by 2-5 hours in one study and by 0·5-4 hours in another.

Three studies detailed the hardware, software and supporting infrastructure requirements of partially-automated contact tracing systems; these included smartphones, tablets, laptops, SIM cards, data plans, high-speed internet and phone battery charging. No study in this section provided cost information and only one detailed implementation duration (10-13 weeks). Li and colleagues reported approximately 230-476 hours/year of contact tracing work was saved by a partially-automated infection control management system in one hospital. In another contact tracers reported that the app-based system ‘was faster and more accurate’ and eliminated substantial travel time (5-6 hours per coordinator daily). Technical support needs, including for training, were a recurrent theme. For example, one study stated that training ‘was often provided by staff who had received only minimal training themselves’ leading to ‘inefficient and incorrect use’; technical expertise was highlighted as an important but limited resource in two others. One study reported that training contact tracers took 2-3 days and another 3 days.
Lessons learnt included the importance of reliable internet and electricity infrastructure,\textsuperscript{30,32} and the value of customising systems based on local priorities.\textsuperscript{30}

3. Other studies relevant to automated contact tracing

We found three studies of contact detection in a relevant disease context but without subsequent tracing or contact notification: one studied students’ smartphone contact patterns\textsuperscript{34}; another integrated radio-frequency contact and virological data\textsuperscript{35} and another used wifi traces to model a hypothetical epidemic.\textsuperscript{36}

None detailed a primary outcome precisely as specified; however, participants in one study\textsuperscript{34} averaged 219 contacts/day with devices of any kind, whilst another\textsuperscript{35} observed 18,765 contact events amongst 84 participants over 11 days (but only 4 influenza transmission events). One study\textsuperscript{34} referred to the need for availability and training of a large study staff. Lessons learnt are detailed in table 2, with further detail in supplementary table S2.\textsuperscript{36,37} No other secondary outcomes were detailed.

Quality assessment

Study quality was variable and quality assessments are detailed in supplementary tables S3-5. The quality of studies in categories 2 and 3 was generally limited by their observational and often descriptive nature, without pre-specified protocols (except in one,\textsuperscript{32} where this was modified during the study). Many were subject to possible confounding, selection bias and selective reporting. Amongst the modelling studies, some (e.g. Ferretti et al.,\textsuperscript{11} Hinch et al.\textsuperscript{24} and Kucharski et al.\textsuperscript{23}) included detailed methods, conducted a range of sensitivity analyses (except one)\textsuperscript{11} and provided their model code. Others provided limited justification of the model structures or assumptions used and did not account for uncertainties or conducted only limited sensitivity analyses.
Discussion

We found no epidemiological studies comparing automated to manual contact tracing systems and their effectiveness in identifying contacts. The modelling studies we identified found that automated contact tracing’s effectiveness depends on both population uptake (e.g. of contact tracing apps) and timeliness of intervention (e.g. quarantining contacts).\textsuperscript{11} Uptake is particularly important since both infectious cases and their contacts need to have and be using a system for it to have any effect, leading to a quadratic relationship such that effectiveness drops off steeply as participation falls. Even under optimistic assumptions (e.g. 75-80\% app uptake amongst smartphone owners and 90-100\% adherence to quarantine), automated contact tracing appears unlikely to achieve control of COVID-19 without concurrent measures;\textsuperscript{23–25} this is even more the case in settings with low smartphone ownership.\textsuperscript{27}

Strengths of this review include the comprehensive search strategy and pre-specified eligibility criteria and screening process. With its focus on outbreak control, it also addresses timely, policy-relevant questions. We quality-assessed all studies, but were unable to undertake meta-analysis and formal assessment of publication bias. Other limitations include the lack of eligible empirical studies of fully-automated contact tracing and a paucity of evidence related to ethical concerns or cost-effectiveness. The modelling studies reflect substantial uncertainty; for example, if environmental transmission (e.g. via droplet contamination of surfaces) of COVID-19 occurs more often than typically assumed by these studies, this would undermine their validity. Given these uncertainties, which relate both to SARS-CoV-2’s transmission and epidemiology and to human behaviour under new, untested scenarios, it is difficult to objectively appraise how realistic the modelling studies’ assumptions (and therefore results) are. Additionally, our review was limited to English-language studies due to short timescales.

Our primary outcomes, regarding numbers and proportions of contacts (including of those who become cases) identified, are a key gap in current evidence, and important metrics for evaluation. The integration and relative impacts of manual and automated systems run in parallel are also
unexamined. Pre-symptomatic transmission may be substantial in COVID-19, making timeliness of quarantine critical. However, the relative timeliness of automated versus manual contact tracing systems is unknown, though partially-automated systems appeared to reduce delays to quarantine. Additionally, whether quarantine adherence differs between automated and manual systems is unknown. Automated notification might be psychologically different from receiving a phone call from a human contact tracer who can give detailed information about what action to take and why, check understanding and address questions or concerns. A previous review found adherence to be extremely variable and influenced by multiple factors, including risk perception and social and financial protections.

Academics have recently warned of automated contact tracing’s risks including ‘mission creep’ towards unprecedented surveillance, and eroded public trust should data be misused or hacked. These are clearly important considerations, although beyond our review’s scope. Trade-offs between privacy and utility are discussed elsewhere and may vary between system architectures, particularly ‘centralised’ systems, which involve data being uploaded to a central server, and ‘decentralised’ systems, which are more strongly privacy-preserving, keeping co-location data on users’ phones. Decentralised systems also benefit from Apple and Google’s support. However, Fraser and colleagues find that centralised systems assess transmission risk more accurately (reducing numbers quarantined), enable better optimisation, are less susceptible to false reports, and more readily evaluated.

Optimising risk thresholds in order to minimise transmission risk and numbers quarantined simultaneously is a key challenge for any contact tracing system, particularly in view of quarantine’s adverse psychological impacts and wider harms. However, this relies on gathering and analysing high-quality data. Where automated contact tracing systems are deployed, they should be evaluated rigorously, including through prospective cohort studies and qualitative studies.
Wider concerns around digital exclusion and broader ethical concerns have been highlighted elsewhere\textsuperscript{18,45} including in the Ada Lovelace Institute review\textsuperscript{17}. Some particularly vulnerable populations (e.g. older and homeless people) are also less likely to own a smartphone, potentially amplifying their risks.\textsuperscript{18,13} Such challenges are more acute still in low-income countries.\textsuperscript{27}

Given substantial remaining uncertainties about automated contact tracing systems’ effectiveness, large-scale manual contact tracing is likely to be required to control COVID-19, alongside automated approaches and other measures such as remote working by a proportion of the population and limiting daily social contacts. Moderate uptake of automated systems could contribute to reducing transmission and could offset some of the work of manual contact tracing. However, such benefits must be weighed against implementation costs and broader risks. Decision-makers should use all available evidence to ensure that contact tracing systems are as effective, equitable and acceptable as possible, and that they are deployed within integrated outbreak responses.

Figure 1: PRISMA Flow diagram (Moher et al. 2009)\textsuperscript{48}
Contributor statement

IB and RWA developed the concept of the review. All authors contributed to the development of the study protocol. Title and abstract screening was performed by two researchers [IB and TC], with 10% of excluded records checked in duplicate. Full-text screening for eligibility was undertaken by two reviewers [IB and MB or TC]. RWA gave an independent view in case of any discrepancies. IB extracted data; this was verified by TC and MB. IB quality appraised studies and produced tables and figure 1. IB wrote the first draft of the manuscript with input from TC, MB and RWA; all authors contributed to drafting and editing the manuscript.

Competing interests

We declare no conflicts of interest.

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Table 1: Summary of study designs, settings, diseases under study and characteristics of populations, interventions and comparators

| Reference, year | Study design | Summary: Name of app/platform | Study setting - e.g. country, region(s) | Disease(s) under study | Study population details (age range; other identifying characteristics) | Number of participants or app users | Automated (no recall or manual data entry) or semi-automated* | Technologie(s) involved (e.g. GPS, Bluetooth) | Device(s) designed for - e.g. web browser, basic mobile phone, smartphone, multiple | Contact definition used/nature of contacts (e.g. recall-based, proximity-based) | Comparator(s) used |
|-----------------|--------------|--------------------------------|------------------------------------------|------------------------|---------------------------------------------------------------------|-----------------------------------|---------------------------------------------|---------------------------------------------|-------------------------------------------------|-------------------------------------------------|------------------|
| Bulchandani et al. 2020 | Modelling study | Branching-tree mathematical model with derivations of mean-field equations for transitions to ‘digital herd immunity’ (i.e. $R_0<1$ due to automated contact tracing) | N/A | COVID-19 | Hypothetical modelled population | N/A | Automated | Not specified | Not specified | Not specified | Non-automated contact tracing (comparisons based on delay to case isolation and contact quarantine) |
| Ferretti et al. 2020 | Modelling study | Modelling study estimating the proportion of transmission from pre-symptomatic individuals (from a series of 40 case pairs), asymptomatic, symptomatic and environmental transmission, and quantifying intervention (case isolation and contact tracing and quarantine) at different delay periods and for different intervention success rates. | N/A | COVID-19 | Hypothetical population network and contact structures, detailed in Fraser et al. (2004)8 | N/A | Automated | Not specified | Smartphone app (standalone) | Location/proximity-based | Other non-pharmaceutical outbreak control intervention |
| Hinch et al. 2020 | Modelling study | Modelling study of multiple outcomes under different scenarios involving app-based contact tracing alongside non-targeted NPIs | UK | COVID-19 | Hypothetical population network and contact structures selected to match age-stratified data reported in Mossong et al. (2008).46 | N/A | Automated | Bluetooth | Smartphone app (standalone) | Proximity-based | Not specified |
| Kim and Paul, 2020 | Modelling study | Mathematical model of automated contact tracing to determine the minimum fraction | Not specified | COVID-19 | Hypothetical population | N/A | Automated | Not specified | Not specified | Proximity-based | Not specified |
| Reference          | Type of study          | Description                                                                 | Location                     | Population Description                                                                 | Contact Tracing Methodology                                                                 | Social Contacts Methodology                                                                 | R0 <1 comparison                                                                 |
|--------------------|------------------------|------------------------------------------------------------------------------|------------------------------|----------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| Kucharski et al. 2020 | Modelling study      | Modelling study of the impact of multiple interventions (including app-based contact tracing, limits on daily contacts and >1 intervention in parallel) on individual-level transmission events | UK                           | Hypothetical population with contact structure based on data from the ‘BBC Pandemic’ study of 40,162 UK participants | Automated                                                                                 | Not specified                                                                            | Smartphone app (standalone)                                                        |
| Xia and Lee, 2020  | Modelling study       | Mathematical model of automated proximity-based contact tracing – derivation of formulae to estimate lower and upper bounds on the minimum adoption rate required to achieve R0<1 | N/A                          | Hypothetical population                                                                 | Automated                                                                                 | Proximity-based (further detail not specified); also discusses use of GPS data            | Smartphone app or standalone wearable device                                       |
| Yasaka et al. 2020 | Modelling study       | Description of TrackCOVID, a decentralised Bluetooth-based contact tracing app including modelling of the population infected at different levels of uptake. | N/A                          | Hypothetical population                                                                 | Automated                                                                                 | Checkpoints based on QR codes                                                          | Smartphone app (standalone)                                                       |
|                    |                        |                                                                              |                              |                                                                                        |                                                                                           |                                                                                           | Face-to-face with manual code scanning                                                  |
|                    |                        |                                                                              |                              |                                                                                        |                                                                                           |                                                                                           | Compared with no contact tracing                                                   |

2) Studies of partially-automated contact tracing

| Reference          | Type of study          | Description                                                                 | Location                     | Population Description                                                                 | Contact Tracing Methodology                                                                 | Social Contacts Methodology                                                                 | R0 <1 comparison                                                                 |
|--------------------|------------------------|------------------------------------------------------------------------------|------------------------------|----------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| Danquah et al. 2019 | Proof-of-concept study with phased introduction | Proof-of-concept observational study regarding the introduction of the Ebola Contact Tracing (ECT) app; details number of contacts identified compared with previous system | Sierra Leone                  | Ebola                                                                                    | Contact tracers and contact tracing coordinators                                         | 86 Contact Tracers, 26 Contact Tracing Coordinators                                    | Manual data entry                                                                 |
|                    |                        |                                                                              |                              |                                                                                        |                                                                                           |                                                                                           | Smartphone app (standalone)                                                        |
|                    |                        |                                                                              |                              |                                                                                        |                                                                                           | Recall-based                                                                            | Other (paper-based system)                                                            |
| Li et al. 2017     | Case study             | Automated identification of contacts within an inpatient setting (lists generated based on user-defined parameters) | Singapore                    | Multiple including influenza A                                                        | Hospital inpatients at Changi General Hospital; system used by IC team                   | Not specified                                                                           | Real-time integration of patient movement and laboratory data                       |
|                    |                        |                                                                              |                              |                                                                                        |                                                                                           |                                                                                           | Computer-based infection control management system                                   |
|                    |                        |                                                                              |                              |                                                                                        |                                                                                           |                                                                                           | Shared room/ concurrent contact/ duration of contact                                   |
|                    |                        |                                                                              |                              |                                                                                        |                                                                                           |                                                                                           | Non-automated contact tracing                                                        |
| Schafer et al. 2016 | Case study             | Case study of app-supported contact tracing using EpiInfo                      | 7 African countries           | Ebola                                                                                    | Used by contact tracers and                                                             | No. of contact tracers not                                                             | Manual data entry                                                                   |
|                    |                        |                                                                              |                              |                                                                                        | Partially-automated                                                                     |                                                                                           | Computer-based                                                                      |
|                    |                        |                                                                              |                              |                                                                                        |                                                                                           | Recall-based                                                                            | Paper-based contact tracing                                                          |
| Study                          | Study Type                  | System Description                                                                                                                                                                                                 | Country | Disease  | Contact Tracing System Used                                                                 | Contact Tracing System Comments                                                                                                                                                                                                 | Data Entry Method | Alerting Method          | Grouping Method             |
|-------------------------------|----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|----------|------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|--------------------------|-----------------------------|
| Sacks et al. 2015             | Case study                 | Case study of the introduction, use and lessons learned from the use of the CommCare contact tracing system in Guinea (c.f. previous paper and Excel-based systems)                                           | Guinea  | Ebola    | 210 contact tracers (of 366 who were trained) to collectively monitor 9,162 contacts.           | Partially-automated                                                                                                                                  | Manual data entry | Smartphone app (standalone) | Recall-based contact tracing system (used in parallel within Guinea by other contact tracers) |
| Tom-Aba et al. 2015           | Case study                 | Case study of the use of an app (ODK Collect app) developed using OpenDataKit and FormHub to support contact tracing in Nigeria. Automated alerting and SMS if any contact met the probable case definition. Also refers to Ebola Sense app (supports follow-up of identified contacts, includes automated search functionality to assign contact tracers). | Nigeria | Ebola    | Used by contact tracers                                                                       | Partially-automated                                                                                                                                  | GPS (for accountability of contact tracers rather than directly within tracing efforts)                                                                                         | Smartphone (or tablet) app (standalone) | Recall-based               | Paper-based contact tracing systems (data manually entered onto a single computer) |
| 3) Studies of automated contact detection in a relevant disease context (without subsequent contact tracing or contact notification) |                           |                                                                                                                                                                                                                  |         |          |                                                                                                                                                     |                                                                                                                                  |                  |                          |                             |
| Aiello et al. 2016 (iEpi sub-study) | Sub-study (descriptive observational study) within a cluster-RCT | iEpi sub-study within a university-based trial; participants given smartphones which were used to detect other study devices as well as nearby Bluetooth-enables devices to map proximity contacts | US      | Influenza | Students aged ≥18                                                                             | Automated contact detection only                                                                                                                                                                                                 | Bluetooth         | Smartphone app (standalone) | Proximity-based contact tracing systems (data manually entered onto a single computer) |
| Study                                      | Methodology                                                                 | Study Design                                                                 | Setting                                                                 | Participants                                                                 | Technology Used                                                                 | Contact Tracing Approach | Data Privacy |
|-------------------------------------------|------------------------------------------------------------------------------|------------------------------------------------------------------------------|------------------------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------|--------------|
| Al Qathrady et al. 2016                    | Observational and modelling (simulation) study                               | Simulation of disease spread and contact tracing using a contact network recreated from WiFi traces; explores different approaches to prioritising investigation/follow-up of at-risk contacts | University faculty and students (contact data based on WiFi use on a university campus across 6 buildings) | WiFi trace data from 34,225 users of 6 University buildings                     | Automated contact detection only                                               | WiFi network traces     | Proximity-based | None         |
| Voirin et al. 2015                         | Proof-of-concept observational study                                        | Observational pilot study combining micro-contact data from wearable proximity sensors and virological data to investigate influenza transmission within an elderly care unit of a hospital | France                                                                  | France Influenza A and B                                                        | Median age (y): 24 - doctors; 30 - nurses; 89 - patients. % female: Doctors - 67%, Nurses - 78%, Patients - 73% | Automated contact detection only | RFID proximity sensors | None         |

*Semi-automated: requires some manual recall by cases of their contacts, manual data-entry into an electronic system with some automated features and/or involvement in informing contacts

**Abbreviations and acronyms:** FIMS: Field Information Management System; QR code: Quick Response code; RCT: Randomised Controlled Trial; RFID (Radio-frequency identification); SORMAS: Surveillance and Outbreak Response Management and Analysis System; US: United States; UK: United Kingdom; WHO: World Health Organization.
| First author (surname), year | Primary outcomes: a) Number or proportion of contacts identified. (observed or required for outbreak control) | Primary outcomes: b) Number or proportion of subsequently diagnosed cases who are identified | Secondary outcomes of interest, including challenges to implementation identified | Other key findings# |
|-----------------------------|-------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|-----------------|
| 1) Bulchandani et al. 2020  | Estimates that approximately 90% app ownership required to achieve epidemic control if 50% of transmission is asymptomatic but no pre-symptomatic transmission. Multiple input parameter values assessed. | Impact on R0 (or other indicators of outbreak control). | Uptake | N/A (modelling study) |
| Ferretti et al. 2020        | Higher uptake, compliance and reduced delays to notification and quarantine improve likelihood of achieving R<1 | Resource requirements or cost-effectiveness | Other ethical issues | Lessons learnt from implementation of the intervention# |
|                             | Propose that such a scheme should fulfill 8 requirements in order to be ethical (see ‘key findings’ in table S2 for further detail). | i. Oversight by an inclusive and transparent advisory board, which includes members of the public. ii. The agreement and publication of ethical principles by which the intervention will be guided. iii. Guarantees of equity of access and treatment. iv. The use of a transparent and auditable | For any given fraction of asymptomatic transmission, and any (non-zero) pre-symptomatic reproduction number ≤R0, there is a critical point of app uptake corresponding to the onset of “digital herd immunity”. This is estimated at 75-95% (depending on the fraction of asymptomatic transmission). | N/A (modelling study) |
| Hinch et al. 2020 | Baseline scenario with a 3-day doubling time and 80% app uptake amongst smartphone owners: approximately 10-15 million people would be quarantined (at any given time, with variation over time). (This is in addition to the over 70 population who are assumed to practice ‘shielding’). | All app configurations modelled resulted in a substantial reduction in new cases, hospital and ICU admissions and a substantial number of lives saved over a 150-day period from the start of a 35-day lockdown, increasing incrementally as uptake increases from 0% to 80% of smartphone owners. Direct contact tracing (first-order contacts only quarantined) suppressed the epidemic only under ‘optimistic’ epidemic growth assumptions (3.5 day doubling time, 5 day generation time); recursive tracing (with first-order contacts) 80% usage to achieve suppression under scenarios 3 and 5 with epidemic doubling time=3.5d, with lower uptake rates reducing incidence | Not reported | N/A (modelling study) | Approximately 100,000 (PCR) tests per day (in the UK) required to permit a smart release from quarantine based on test results of the index case. |
throughout. household members also quarantined) achieved epidemic control under pessimistic assumptions but only leads to a 50% reduction in numbers quarantined c.f. full lockdown.

| Study | Details |
|-------|---------|
| Kim and Paul, 2020 | • Under a range of assumptions, the percentage of the population needed to be enrolled in automated contact tracing for outbreak control \( R_e < 1 \) is estimated. As an example, 40-60% uptake required for \( R_e < 1 \), assuming a 30% average transmission probability per contact event, if 75-95% actively confirm when they get infected. The authors conclude that ‘in real-world scenarios, automated contact tracing alone cannot contain a pandemic driven by a pathogen like SARS-CoV-2’ (see supplementary table S2 for further detail). |
| Kucharski et al. 2020 | Median number of contacts successfully traced and quarantined (assuming 90% of those traced are quarantined) per case (modelled results): 4 (mean 14) via automated contact tracing, 21 per case (mean 32) via manual contact tracing (acquaintances only) and 28 per case (mean 39) with all contacts. App-based contact tracing would require a high level of coverage to ensure \( R_e < 1 \). App-based contact tracing achieves a smaller relative reduction in \( R_e \) than manual contact tracing for either all contacts or acquaintances only, varying with % symptomatic and relative role of asymptomatic transmission (fig S2 in the paper). Estimate 53% uptake (as an input parameter) across UK population in baseline ‘optimistic’ scenario, based on 75% uptake x 71% smartphone ownership. Not reported |

- Reducing the transmission probability (per contact episode) and the increasing fraction of infected individuals that test positive can assist in reducing the burden on automated contact tracing.
- Estimate that at least 30–50 additional tests would be required for each case detected (meaning a large volume required daily if incidence high).
- Individual-level variation in transmission and contact networks are important considerations, as high variation can lead to superspreading events.
- Find that gatherings in other settings needed to be restricted to relatively
| Study                                      | Methodology | Uptake Assumptions | Contact Tracing Effectiveness | Technical Issues and Challenges | Notes                                                                 |
|-------------------------------------------|-------------|--------------------|-------------------------------|--------------------------------|----------------------------------------------------------------------|
| Xia and Lee, 2020                         | Not specified – assumes 100% identification of contacts | Not specified/unclear | Assessment of the minimum uptake required to achieve R0<1. Estimates this at 95%-100% (if only 2-10% of cases are detected due to a large proportion being mild or asymptomatic) | Not reported | N/A (modelling study) |
| Yasaka et al. 2020                        | Not specified | Not specified | No summary estimates presented; based on results presented graphically, an estimated 65-90% of the population would be infected at the epidemic curve peak with no (0%) uptake of the automated contact tracing app. and 15-50% for an adoption rate of 75%. | The authors speculate that the app’s lack of a user registration process can be expected to improve adoption rates | The authors state that due to reduced data sharing “government agency overhead would be minimal.” |
| Danquah et al. 2019                       | Mean 36/case with app-based system; 16/case with paper-based system | Not specified; data suggest no identified contacts developed Ebola (however, only 69% of contacts were visited) | Training contact tracers took 3 days. Contact tracers reported that the app-based system ‘was faster and more accurate’. Reduced travel time (by 5-6 hours/coordinator per day). Battery charging and technical support both important. | | Proposes use of an individual-specific QR code to verify that a diagnosis is confirmed, which only be generated by ‘authorised users’. Further, QR code scanning approach suggested requires user motivation – “users may become fatigued from such behaviour over time and choose to discontinue or may be dissuaded from participating at the onset.” |

2) 

Technical issues incl. poor network coverage; battery life and quality of phones
Further training on syncing data between phone and server needed
Compensation and planning for phone charging, including travel to charging booths.
| Li et al. 2017 | Reduced delay to intervention by the hospital IC team by 0.5-4 hours | - | 230-476 hours of contact tracing time saved/annum (baseline unclear) | - | The authors state that "implementation (of the new system) took significant time and effort from users." Where 'some specific data analytics and workflow processes were not available' within the infection control management software, this necessitated workflow changes or workarounds. Some epidemiologically important organisms (e.g. Influenza A virus, RSV) were tracked for the first time. |
|----|-----------------|---|-----------------|---|-------------------------------------------------|
| Schafer et al. 2016 | More than 50,000 contacts recorded on system for >100,000 cases by end 2015 | Not specified | Widely used by contact tracers in these settings, % not specified | - | Technical expertise to support training was limited, leading to 'inefficient and incorrect use'. Data-management staff who are well trained on use of the application were also identified as an important requirement for successful implementation, but the availability of staff with these skills or training was often lacking. Time and expertise required for set-up and - | A lesson learned identified by the authors is that successful use of the application in a given location required organized flow of information on individual contacts between data managers and contact tracers, and a concerted effort to use the application; both of these were often not the case however. The authors state: 'In most affected locations, minimal if any IT support was available.' Epi Info VHF was 'originally designed to require minimal IT support.' The EpInfo VHF app's contact tracing features 'were only used to their full extent in a few locations'. There was often reluctance to change from preexisting paper-based systems.' Technical issues and problems related to insufficient infrastructure were often (incorrectly) attributed to the Epi Info VHF (Viral Haemorrhagic Fever) application itself. The authors also highlight that, compared to comparator systems, the EpInfo VHF app-supported system:
| Sacks et al. 2015 | 210 contact tracers monitoring 9,162 contacts | Not specified | 210 of the 366 who were trained on CommCare actively used it; |
|------------------|-----------------------------------------------|--------------|---------------------------------------------------------------|
|                  | Total time to establish programme: 10-13 weeks; training contact tracers took 2-3 days. Smartphones, SIM cards, 500MB data/month and solar phone chargers donated for staff use. Need for technical support. | - | - |
|                  | Acknowledgement of the challenges inherent in adopting a new technology during a during complex emergency; the authors argue that 'innovation to disrupt the status quo may be integral to controlling long-standing epidemics', but also that feasibility and risks versus benefits should be carefully considered and, where a new technology is implemented, it support', but requirements for 'multiuser data entry (and therefore database servers and networks)… expanded system complexity and support requirements'. Accommodating multiple countries' needs within 1 software product presented challenges: 'the fragmented response resulted in a lack of coordination and oversight regarding the data elements collected in each country' such that 'each country developed a slightly different version'. | - | - |
|                  | Availability and cost of expertise for specific software used | - | - |
|                  | Recruitment of local tech-savvy youth volunteers helped to accelerate phone configuration. | - | - |
|                  | Actual use of the data by government staff members to inform action was limited. | - | - |
|                  | Clearer initial standards [for contact tracing protocols and metrics] could have accelerated the design process. | - | - |
|                  | 86% agreement in second round of validation against reference database derived from paper-based forms (78% in the first round). Additional benefits identified: Pre-set contact tracing algorithms can guide a contact tracer through visits | - | - |
|                  | Real-time performance data can inform contact tracing supervisors | - | - |
|                  | Multimedia files useful for sensitization and training | - | - |
| Tom-Aba et al. 2015 | Not specified | Not specified | Reduced delay to evacuation of symptomatic contacts from their homes to an isolation facility from 3-6 hours to 1 hour, with associated benefits for outbreak control. | - | Costs of android phones, tablets, laptops, data plans, and high-speed internet, time costs of trained personnel. | - | Improvement in contact follow-up rates (from 90-99% to consistently 100%) after introduction); however concurrent factors may also explain this |
|-------------------|--------------|--------------|-------------------------------------------------------------------------------------------------|---|---------------------------------------------------------------------------------------------------------------------------------|---|-----------------------------------------------------------------------------------|
| 3) Aiello et al. 2016 | 453,281 total Bluetooth contacts between iEpi substudy smartphones only, and 1591,741 with other devices over 78 days (62.5 and 219.4 contacts/phone/day respectively) | N/A | - | ● Required availability and training of a large study staff (size not specified).  
● The automated contact detection system implemented required mapping, debugging, data cleaning and verification. | - | ● 95.2% participated due to the cash incentive |
| Al Qathrady et al. 2016 | 353,458 encounter records from 34,225 users over one week | Not specified | All contacts within the simulated institutional outbreak could be traced based on one infectious case having been identified (for an infection with a latent period of 1 day and infectious period of 2 days); further detail not provided | - | Accuracy of the contact tracing system in some buildings decreased with coverage, but increased in others. This is due to differences in the encounter patterns of population in each building, and the node chosen as the source of the modelled infection. | The tracing system can identify all infected cases even if it starts the tracing process only knowing one case. Prioritisation of contacts for testing is more accurate (up to ~80% accuracy) when adopting either of two selection strategies; encounter infection probability, based on cumulative probability of infection based on previous recorded encounters with infected individuals, or a 'mostly named' strategy |
| Author(s)          | Description                                                                 | Details                                                                 |
|-------------------|-----------------------------------------------------------------------------|------------------------------------------------------------------------|
| Voirin et al. 2015 | 18,765 contact events recorded amongst 84 individuals over 11 days (cumulative duration 251 hours) | Not specified, Not reported, • Most contacts between nurses or between nurses and a patient. • Influenza transmission is difficult to predict based on contact data alone. |

*See supplementary information for additional detail.*

**Abbreviations:** c.f.: compared with; IC: infection control; N/A: not applicable; QR code: Quick Response code; R₀: basic reproduction number; Reₚ: effective reproduction number; UK: United Kingdom; US: United States