nature medicine

REVIEW ARTICLE

https://doi.org/10.1038/s41591-020-1011-4

Digital technologies in the public-health response to COVID-19

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Digital technologies are being harnessed to support the public-health response to COVID-19 worldwide, including population surveillance, case identification, contact tracing and evaluation of interventions on the basis of mobility data and communication with the public. These rapid responses leverage billions of mobile phones, large online datasets, connected devices, relatively low-cost computing resources and advances in machine learning and natural language processing. This Review aims to capture the breadth of digital innovations for the public-health response to COVID-19 worldwide and their limitations, and barriers to their implementation, including legal, ethical and privacy barriers, as well as organizational and workforce barriers. The future of public health is likely to become increasingly digital, and we review the need for the alignment of international strategies for the regulation, evaluation and use of digital technologies to strengthen pandemic management, and future preparedness for COVID-19 and other infectious diseases.

COVID-19, a previously unknown respiratory illness caused by the coronavirus SARS-CoV-2[1,2], was declared a pandemic by the World Health Organization (WHO) on 11 March 2020, less than 3 months after cases were first detected. With now over 9.8 million confirmed cases and more than 495,000 deaths[3] recorded worldwide, there are grave concerns about the global health, societal and economic effects of this virus, particularly on vulnerable and disadvantaged populations, and in low- and middle-income countries with fragile health systems[4,5]. At the time of this writing, 7.1 billion people live in countries that have had substantial travel and social restrictions[6].

As with the control of outbreaks and pandemics before it, controlling the COVID-19 pandemic rests on the detection and containment of clusters of infection and the interruption of community transmission to mitigate the impact on human health. During the plague outbreak that affected 14th-century Europe, isolation of affected communities and restriction of population movement were used to avoid further spread[7]. These public-health measures for outbreak response remain relevant today, including surveillance, rapid case identification, interruption of community transmission and strong public communication. Monitoring how these measures are implemented and their impact on incidence and mortality is essential.

All countries are required by the International Health Regulations (2005)[8] to have core capacity to ensure national preparedness for infectious hazards that have the potential to spread internationally. Research and development of new methods and technologies to strengthen these core capacities often occurs during outbreaks, when innovation is an absolute necessity[9]. During the outbreak of severe acute respiratory syndrome in 2003, Hong Kong identified clusters of disease through the use of electronic data systems[10]. During the Ebola outbreaks in West Africa in 2014–2016, mobile phone data were used to model travel patterns[11], and hand-held sequencing devices permitted more-effective contact tracing and a better understanding of the dynamics of the outbreaks[12]. Similarly, digital technologies also have been deployed in the COVID-19 pandemic[13,14] (Table 1) to strengthen each of the four public-health measures noted above.

The digital revolution has transformed many aspects of life. As of 2019, 67% of the global population had subscribed to mobile devices, of which 65% were smartphones—with the fastest growth in Sub-Saharan Africa[15]. In 2019, 204 billion apps were downloaded[16], and as of January 2020, 3.8 billion people actively used social media[17].

Here we critically review how digital technologies are being harnessed for the public-health response to COVID-19 worldwide (Fig. 1). We discuss the breadth of innovations and their respective limitations. This systems-level approach is needed to inform how digital strategies can be incorporated into COVID-19-control strategies, and to help prepare for future epidemics.

Digital epidemiological surveillance

A core public-health function of outbreak management is understanding infection transmission in time, place and person, and identifying risk factors for the disease to guide effective interventions. A range of digital data sources are being used to enhance and

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Table 1 | Digital technologies used in the COVID-19 pandemic

Public-health need	Digital tool or technology	Example of use	Refs.
Digital epidemiological surveillance	Machine learning	Web-based epidemic intelligence tools and online syndromic surveillance	Web-based epidemic intelligence tools: 20–23,25 Based on social media or online search data: 30–33
	Survey apps and websites	Symptom reporting	37,38,48,49
	Data extraction and visualization	Data dashboard	39–45
Rapid case identification	Connected diagnostic device	Point-of-care diagnosis	58
	Sensors including wearables	Febrile symptoms checking	51–53
	Machine learning	Medical image analysis	65,66
Interruption of community transmission	Smartphone app, low-power Bluetooth technology	Digital contact tracing	Paper: 71 Apps: 76–79 Frameworks: 81–83
	Mobile-phone-location data	Mobility-pattern analysis	Analysis: 84,87–89,93 Datasets: 86,90,91,122
Public communication	Social-media platforms	Targeted communication	104,107
	Online search engine	Prioritized information	105
	Chat-bot	Personalized information	110
Clinical care	Tele-conferencing	Telemedicine, referral	50

Summary of digital technologies deployed in public-health interventions for the COVID-19 outbreak, showing key publications, examples and resources.

interpret key epidemiological data gathered by public-health authorities for COVID-19.

Online data sources for early disease detection. Established population-surveillance systems typically rely on health-related data from laboratories, notifications of cases diagnosed by clinicians and syndromic surveillance networks. Syndromic surveillance networks are based on reports of clinical symptoms, such as ‘influenza-like illness’, rather than a laboratory diagnosis, from hospital and selected sentinel primary and secondary healthcare facilities, which agree to provide regular surveillance data of all cases. These sources, however, ultimately miss cases in which healthcare is not sought. In the UK, for example, where until recently only hospitalized patients and healthcare workers were routinely tested for COVID-19, confirmed cases represent an estimated 4.7% of symptomatic COVID-19 cases[18]. Identifying undetected cases would help elucidate the magnitude and characteristics of the outbreak[19] and reduce onward transmission.

In the past two decades, data from online news sites, news-aggregation services, social networks, web searches and participatory longitudinal community cohorts have aimed to fill this gap. Data-aggregation systems, including ProMED-mail[20], GPHIN[21], HealthMap[22] and EIOS[23], which use natural language processing and machine learning to process and filter online data, have been developed to provide epidemiological insight. These data sources are increasingly being integrated into the formal surveillance landscape[24] and have a role in COVID-19 surveillance. The WHO’s platform EPI-BRAIN brings together diverse datasets for infectious-disease emergency preparedness and response, including environmental and meteorological data[25]. Several systems have claimed detection of early disease reports for COVID-19, through the use of crowdsourced data and news reports, before the WHO released a statement about the outbreak[14,20,26]. The UK’s automatic syndromic surveillance system scans National Health Service digital records[27] to pick up clusters of a respiratory syndrome that could signal COVID-19. There is also interest in using online data to estimate the true community spread of infectious diseases[28,29]. Preliminary work on the epidemiological analysis of COVID-19-related social-media content has been reported[30–32]. Models for COVID-19 (ref. [33]), building on previously established internet search algorithms for influenza[34], are included in Public Health England’s weekly reports[35].

Crowdsourcing systems used to elucidate the true burden of disease are also supporting syndromic surveillance. InfluenzaNet gathers information about symptoms and compliance with social distancing from volunteers in several European countries through a weekly survey[36]. Similar efforts exist in other countries, such as COVID Near You[37] in the USA, Canada and Mexico. The COVID-19 symptom-tracker app has been downloaded by 3.9 million people in the UK and USA[38] and is feeding into national surveillance. While rapid and informative, these systems can suffer from selection bias, over-interpretation of findings and lack of integration with official national surveillance that report established surveillance metrics. A fragmented approach has meant that there are 39 initiatives in the UK alone that are collecting symptoms from people in the community, with no centralized data collection (M. Edelstein, personal communication).

Data-visualization tools for decision support. Data dashboards are being used extensively in the pandemic, collating real-time public-health data, including confirmed cases, deaths and testing figures, to keep the public informed and support policymakers in refining interventions[39–41]. COVID-19 dashboards typically focus on time-series charts and geographic maps, ranging from region-level statistics to case-level coordinate data[40,42]. Several dashboards show wider responses to the pandemic, such as clinical trials[43], policy and economic interventions[44] and responses to social-distancing directives[45]. Few dashboards include data on contact tracing or community surveillance from apps or their effectiveness. Challenges with the quality and consistency of data collection remain a concern. Lack of official standards and inconsistencies in government reporting of statistics across countries make global comparisons difficult. Up-to-date and accurate offline statistics from governments are also not always accessible. Novel visualization approaches are emerging, such as the NextStrain open repository, which presents viral sequence data to create a global map of the spread of infection[41]. This is enabled by open sharing of data and is based on open-source

Fig. 1 | The interconnected digital technologies used in the public-health response to COVID-19. Many approaches use a combination of digital technologies and may rely on telecommunications infrastructure and internet availability. Machine learning is shown as a separate branch for clarity, although it also underpins many of the other technologies. Much of the data generated from these technologies feeds into data dashboards. SMS, short message service.

code. Such speed of the sharing of such data has not been witnessed in previous global outbreaks[46].

Rapid case identification

Early and rapid case identification is crucial during a pandemic[47] for the isolation of cases and appropriate contacts in order to reduce onward spread and understand key risks and modes of transmission. Digital technologies can supplement clinical and laboratory notification, through the use of symptom-based case identification and widespread access to community testing and self testing, and with automation and acceleration of reporting to public-health databases.

Case identification by online symptom reporting, as seen in Singapore[48] and the UK[49], is traditionally used for surveillance, but it now offers advice on isolation and referrals to further healthcare services, such as video assessments[50] and testing. These services can be rapidly implemented but must be linked to ongoing public-health surveillance and to action, such as isolation of cases and quarantining of contacts. Although this approach is suitable for symptomatic people, widespread testing of people and populations, as well as contact tracing, has a crucial role in case identification, as an estimated 80% of COVID-19 cases are mild or asymptomatic[19]. Sensors, including thermal imaging cameras and infrared sensors, are being deployed to identify potential cases on the basis of febrile symptoms (for example, at airports). The large numbers of false-positive and false-negative results mean that this is unlikely to have a substantial effect beyond increasing awareness[51,52]. Wearable technologies are also being explored for monitoring COVID-19 in populations[53].

There has been increasing interest in decentralized, digitally connected rapid diagnostic tests to widen access to testing, increase capacity and ease the strain on healthcare systems and diagnostic laboratories[54–56]. Several point-of-care COVID-19 PCR tests are in development[57,58]; however, their use is still limited to healthcare settings. Drive-through testing facilities and self-swab kits have widened access to testing. There are inherent delays between sampling, sending samples to centralized labs, waiting for results and follow-up. By contrast, point-of-care rapid diagnostic antibody tests could be implemented in home or community or social-care settings and would give results within minutes. Linking to smartphones with automatic readout through the use of image processing and machine-learning methods[59,60] could allow mass testing to be linked with geospatial and patient information rapidly reported to both clinical systems and public-health systems and could speed up results. For this to work effectively, standardization of data and integration of data into electronic patient records are required.

Identifying past infections by antibody testing is also central to population-level surveillance and evaluating the efficacy of interventions such as social distancing. So far, point-of-care serology tests in particular have variable performance, and in light of the possibility that antibody responses may be short-lived, how such testing can assist in patient management remains unclear[61–63]. Some have argued that seropositive workers who must remain active in the economy could receive a digital 'immunity passport' to demonstrate protection from infection, although such a strategy is fraught with operational and clinical uncertainty[63,64]. Machine-learning algorithms are also being developed for case identification by automated

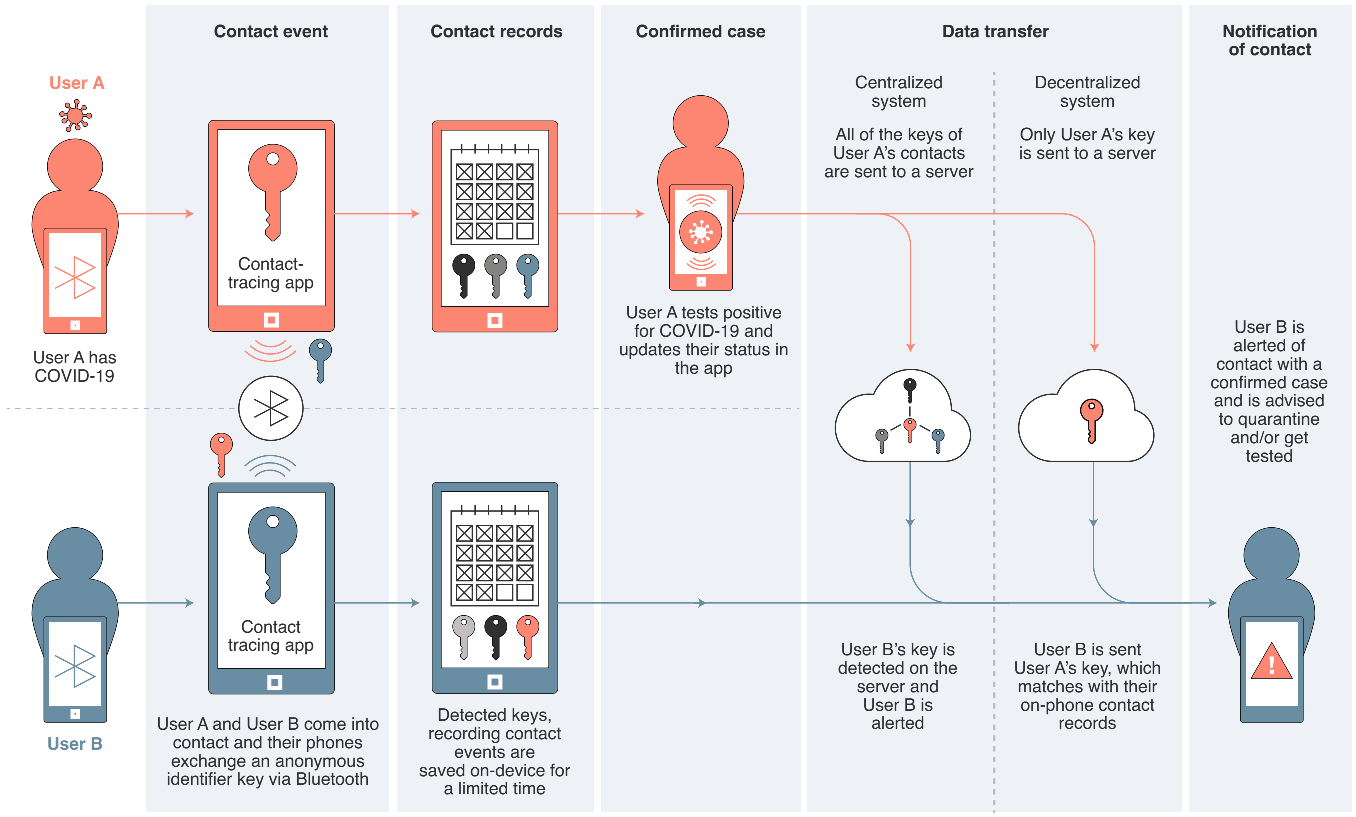

Fig. 2 | Contact tracing for COVID-19 with Bluetooth-enabled smartphone apps. Proximity-detecting contact-tracing apps use Bluetooth signals emitting from nearby devices to record contact events. Centralized apps share information about contacts and contact events with a central server. The centralized TraceTogether app[72] uploads information when a user reports testing positive for COVID-19. Some centralized Bluetooth-enabled contact-tracing apps upload the contact graph for all users[148]. Decentralized apps, such as SwissCovid[149], upload only an anonymous identifier of the user who reports testing positive for COVID-19. This identifier is then broadcast to all users of the app, which compares the identifier with on-phone contact-event records.

differentiation of COVID-19 from community-acquired pneumonia through the use of hospital chest scans by computerized tomography[65–67]. Further evaluation of their utility is recommended[68,69].

Interrupting community transmission

After case identification and isolation, rapid tracing and quarantining of contacts is needed to prevent further transmission[70]. In areas of high transmission, the implementation and monitoring of these interventions is needed at a scale that is becoming increasingly unfeasible or at least challenging by traditional means[71].

Digital contact tracing. Digital contact tracing automates tracing on a scale and speed not easily replicable without digital tools[71]. It reduces reliance on human recall, particularly in densely populated areas with mobile populations. In the COVID-19 pandemic, digital contact-tracing apps have been developed for use in several countries; these apps rely on approaches and technologies not previously tried on this scale and are controversial in terms of privacy. Evaluating their accuracy and effectiveness is essential.

Early digital tracing initiatives raised concerns about privacy[72]. In South Korea, contacts of confirmed cases were traced through the use of linked location, surveillance and transaction data[73]. In China, the AliPay HealthCode app automatically detected contacts by concurrent location and automated the enforcement of strict quarantine measures by limiting the transactions permitted for users deemed to be high risk[74,75]. More-recent voluntary contact-tracing apps have been launched in collaboration with governments; these collect location data by global positioning system (GPS) or cellular networks[76], proximity data collected by Bluetooth[72,77] or a combination of those[78,79]. Concerns have been raised about centralized systems (Fig. 2) and GPS tracking. Norway halted the use of and data collection from its Smittestopp app after the country's data-protection watchdog objected to the app's collection of location data as 'disproportionate to the task', and they recommended a Bluetooth-only approach[80]. Several international frameworks with varying levels of privacy preservation are emerging, including Decentralized Privacy-Preserving Proximity Tracing[81], the Pan-European Privacy-Preserving Proximity Tracing initiative[82] and the joint Google–Apple framework[83].

A key limitation of contact-tracing apps is that they require a large proportion of the population to use the app and comply with advice for them to be effective in interrupting community transmission (effective reproduction number (R), <1)[71]. Placing this in perspective, national uptake of the TraceTogether app in Singapore had reached only 30% as of June 2020 (ref. [72]). Adoption is also limited by smartphone ownership, user trust, usability and handset compatibility. Key practical issues remain, such as understanding which contacts are deemed to be close enough for transmission and when exposure time is considered long enough to trigger an alert. System effectiveness in identifying transmission events is not well described, and it is therefore arguable that human interpretation is still important.

Evaluating interventions through the use of mobility data. Aggregated location data collected by smartphones via GPS, cellular network and Wi-Fi can monitor real-time population flows[84], identify potential transmission hotspots and give insight into the effectiveness of public-health interventions such as travel

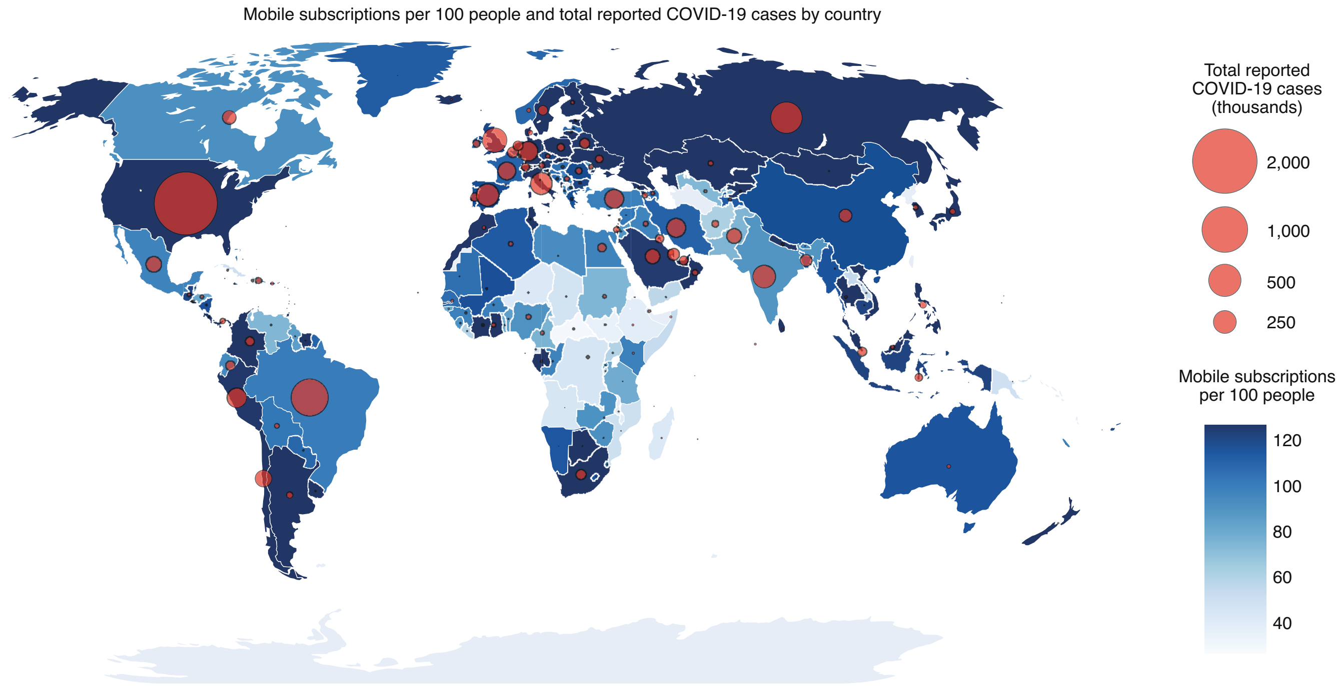

Fig. 3 | The global reach of mobile phones to areas affected by COVID-19. Mobile subscriptions per 100 people (blue; International Telecoms Union[150], 2018) and reported COVID-19 cases by country (red; WHO[151], 8 June 2020). COVID-19 is a global pandemic, yet some countries may be better resourced than others to respond with digital health interventions. There may be intra-country inequalities in mobile subscription rates. Case detection and reporting practices differ among countries, with variable under-reporting of true cumulative case counts.

restrictions on actual human behavior. Access to mobility data is a major challenge, and these approaches have raised ethical and privacy concerns[85].

Mobility data with privacy-preserving aggregation steps have recently been made available by several technology and telecom companies for the purposes of COVID-19 control; however, the datasets are limited and there is no long-term commitment in place for data sharing. Daily aggregated origin-destination data from Baidu[86] are being used to evaluate the effect of travel restrictions[87] and quarantine measures[88] on COVID-19 transmission in China. Analysis of the location data of Italian smartphone users estimated a reduction of 50% in the total trips between Italian provinces in the week after the announcement of lockdown on 12 March 2020 (ref. [89]). Google has released weekly mobility reports with sub-national granularity, including breakdown by journey type and destination (such as workplaces and parks), and has made their dataset publicly downloadable[90]. Apple has similarly released a dataset with daily figures for mobility and assumed method of transport[91]. There is no standardization of these datasets between providers, however, and not all countries or regions are included in these datasets.

Assessing local differences in mobility and contact patterns may be critical for predicting the heterogeneity of transmission rates between different communities and in different regions in which household size and age-stratified contact patterns may differ. This contextual information can provide insight into the effect of interventions to slow transmission, including the impact of handwashing[92], social distancing and school closures[93]. The monitoring of social-distancing measures could also be used to forecast health-system demands[94] and will be important in assessing the easing of restrictions when appropriate. Concerns have been raised over breaches of civil liberties and privacy when people are tracked to monitor adherence to quarantine and social distancing, including the use of wearable devices[95] and drones[96].

Public communication: informing populations

Effective implementation of interventions during a pandemic relies on public education and cooperation, supported by an appropriate communications strategy that includes active community participation to ensure public trust. With 4.1 billion people accessing the internet[97] and 5.2 billion unique mobile subscribers[15], targeted communication through digital platforms has the potential to rapidly reach billions and encourage community mobilization (Fig. 3). Key challenges persist, including the rise of potentially harmful misinformation[98,99] and digital inequalities[100] (discussed below).

Online data and social media have had an ongoing, important role in public communication[101] since the first reports of an unusual influenza-like illness resistant to conventional treatment methods emerged in China[102]. Public-health organizations and technology companies are stepping up efforts to mitigate the spread of misinformation[103,104] and to prioritize trusted news sites; for example, Google's SOS alert intervention[105] prioritizes the WHO and other trusted sources at the top of search results. There are few reports about the impact of these interventions[106,107] and difficulties in defining misinformation[108]. A United Nations study found that 86% of member states had placed COVID-19 information on national websites by early April 2020 (ref. [109]), and many are using text messaging to reach populations who do not have access to the internet. Chat-bots are also providing information to reduce the burden on non-emergency health-advice call centers[110], and clinical practice is being transformed by the rapid adoption of remote health-service delivery, including telemedicine, especially in primary care[50]

Digital communication platforms are also supporting adherence to social-distancing measures. Video conferencing is allowing people to work and attend classes from home[111], online services are supporting mental health[112] and digital platforms are enabling community-mobilization efforts by providing ways to assist those in need[113]. Nevertheless, the security and privacy of freely available

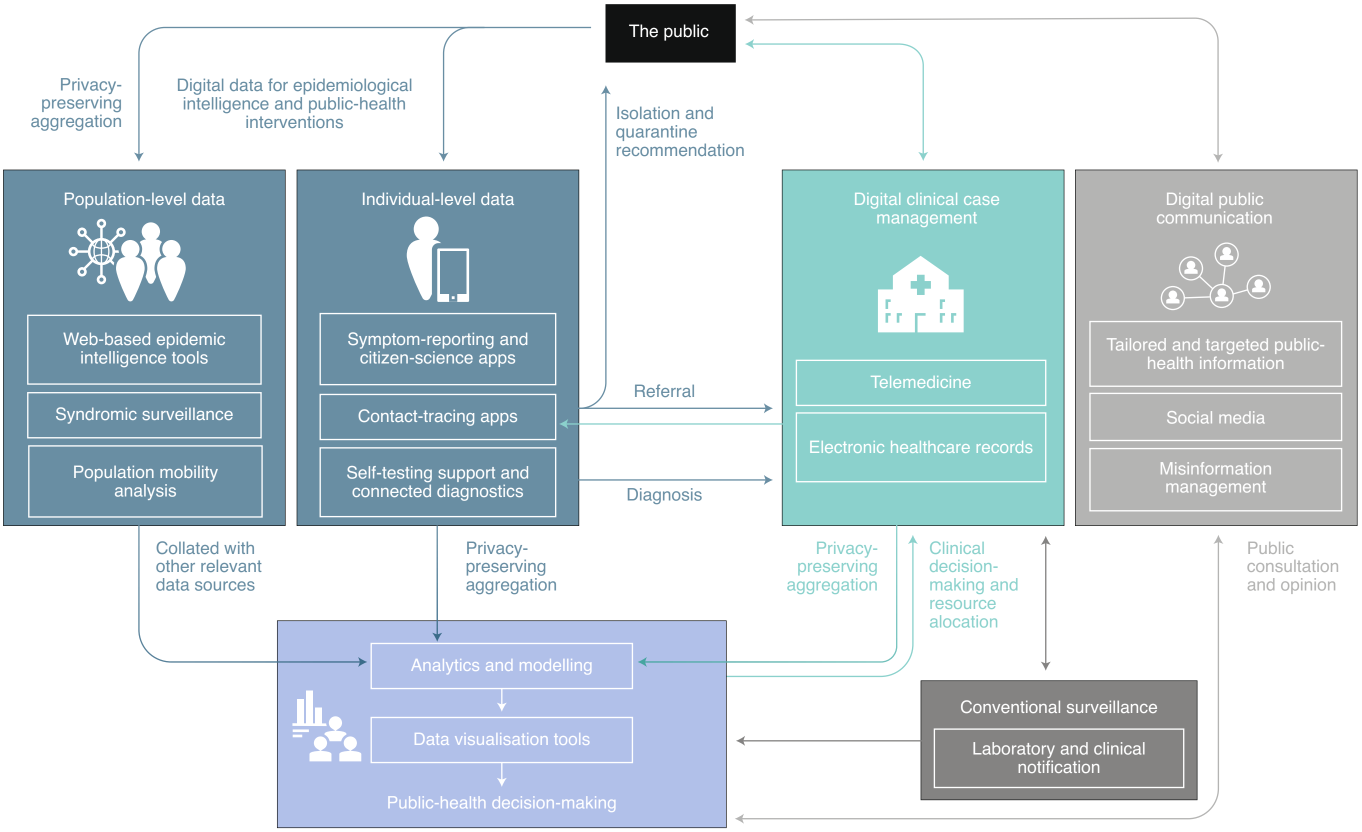

Fig. 4 | The flow of information in a digitally enabled and integrated public-health system during an infectious-disease outbreak. Digital data are created by the public, both at the population level and at the individual level, for epidemiological intelligence and public-health interventions, and for the support of clinical case management. They are also informed by conventional surveillance via laboratory and clinical notification. This feeds into public-health decision-making and communication with the public through digital channels. Other relevant sources of information include population, demographic, economic, social, transport, weather and environmental data.

communication platforms remains a concern, particularly for the flow of confidential healthcare information.

Future directions

Digital technologies join a long line of public-health innovations that have been at the heart of disease-prevention-and-containment strategies for centuries. Public health has been slower to take up digital innovations than have other sectors, with the first WHO guidelines on digital health interventions for health-system strengthening published in 2019 (refs. [114,115]). The unprecedented humanitarian and economic needs presented by COVID-19 are driving the development and adoption of new digital technologies at scale and speed. We have highlighted the potential of digital technologies to support epidemiological intelligence with online datasets, identify cases and clusters of infections, rapidly trace contacts, monitor travel patterns during lockdown and enable public-health messaging at scale. Barriers to the widespread use of digital solutions remain.

Implementation. Digital technologies cannot operate in isolation and need to be integrated into existing public healthcare systems[116]. For example, South Korea and Singapore successfully introduced contact-tracing apps to support large teams of manual contact tracers as one of many measures, including strict isolation of cases and quarantine[73].

Digital data sources, like any data source, need to be integrated and interoperable, such as with electronic patient records. Analysis and use of these data will depend on the digital infrastructure and readiness of public-health systems, spanning secondary, primary and social-care systems. The logistics of delivery to ensure population impact are often given too little attention and can lead to over-focus on the individual technology and not its effective operation in a system. The coordination of interventions is also a challenge, with multiple symptom-reporting sites in a single country, which risks fragmentation.

Looking ahead, there is a need for a systems-level approach for the vision of the ideal fit-for-purpose digital public-health system[117] that links symptom-tracking apps, rapid testing and case isolation, contact tracing and monitoring of aggregated population-mobility levels, access to care and long-term follow-up and monitoring, with public communication (Fig. 4). These types of integrated online care pathways are not new concepts, having been shown to be highly acceptable and feasible for other infectious diseases, such as chlamydia[118].

Data sharing and data quality. Big-data and artificial-intelligence approaches are only as good as the empirical datasets that are put into them, yet detailed public-health and private datasets are often inaccessible, due to privacy and security concerns, and often lack standardized formats or are incomplete. Researchers are calling for technology and telecom companies to share their data in a 'proportionate, ethical and privacy-preserving manner'[85,119,120], often citing a moral imperative for these companies to contribute where there is justification for data use. Some companies are making subsets of aggregated data available[86,90,91,121,122]. These data are not consistent and are not provided within the same timeframe, and there is no standard format or long-term commitment. Researcher-led international collaborations have aimed to aggregate multiple international data sources of voluntarily reported information[41,123].

Equally, governments should provide much greater transparency in their datasets, including epidemiological data and risk factors for acquisition, with downloadable formats for researchers. Several governments have made available de-personalized individual-level datasets for research purposes[124,125], although this raises potential privacy concerns. Open-source data, code and scientific methods are being rapidly and widely shared online, including increased use of preprints, which speed up data availability but lack peer review[126].

Evidence of effectiveness and regulation. Evidence of the effectiveness of any new technology is needed for wider adoption, but as the current pandemic is ongoing, many digital technologies have not yet been peer-reviewed, been integrated into public-health systems, undergone rigorous testing[127] or been evaluated by digital health-evidence frameworks, such as the evidence standards framework for digital health technologies of the National Institute for Health and Care Excellence[128]. Contact-tracing apps have been launched in at least 40 countries[129], but there is currently no evidence of the effectiveness of these apps[130], such as the yield of identified cases and contacts, costs, compliance with advice, empirical estimates of a reduction in the R value or a comparison with traditional methods. Although it is challenging, due to the urgency of the pandemic, evaluation of the effectiveness of interventions is essential. Researchers, companies and governments should publish the effectiveness of their technologies in peer-reviewed journals and through appropriate clinical evaluation.

There is an urgent need for coordinated international digital public-health strategies, but these have been slow to emerge. On 22 March 2020, the WHO release a draft of its global strategy on digital health for 2020–2024 (ref. [131]). On 8 April, the European Union called for a pan-European approach on the use of apps and mobile data for COVID-19[82,132].

Legal, ethical and privacy concerns. Highly granular or personal data for public-health surveillance raises legal concerns[133], ethical concerns[134,135] and security and privacy concerns[136]. Not all digital interventions have allowed consensual adoption or have made the option of consent for specific purposes explicit[75], and some have been used to enforce measures as well as to monitor them. In many cases, widespread adoption is related to effectiveness, which highlights the need for public trust and engagement. There is concern that emergency measures set precedent and may remain in place beyond the emergency, which will lead to the ongoing collection of information about private citizens with no emergency-related purpose[137,138]. All systems will need to be 'proofed' against invasions of privacy and will need to comply with appropriate legal, ethical and clinical governance[75]. Data can be shared under a legal contract for a well-defined purpose and time, with requirements for independent audit[139] to ensure data are not used for purposes outside of the pandemic. Dynamic consent processes could also allow users to share their data, and privacy-preserving technologies, such as differential privacy and homomorphic encryption, could ensure that access is possible only for specific purposes and is available in a tamper-proof manner[13,140] to allow auditing.

Inequalities and the digital divide. In 2018, the World Health Assembly Resolution on Digital Health recognized the value of digital technologies in advancing universal health coverage and the Sustainable Development Goals. Although trends are narrowing, today there remains a digital divide, and 51% of the world's population does not subscribe to the mobile internet[15]. The lack of access to mobile communications is seen in low- and middle-income countries, although people with lower socio-economic status in high-income countries are also affected[141]. The Pew Research Center reported large disparities between people 18–29 years of age and those over 50 years of age in their mobile-communication access[142]. There are also reports of restricted mobile internet access, such as in areas of Myanmar, which have left some populations unware of the pandemic[143]. This outbreak has also disproportionately affected some communities, such as Black and minority ethnic groups, more than others[144]. It is therefore essential to develop tools and messaging that are accessible[100] and can be tailored to specific risks, languages and cultural contexts.

Workforce and organizational barriers. The spread of the COVID-19 pandemic has exposed the need for government leadership to accelerate the evaluation and adoption of digital technologies. Successful implementation strategies will require carefully accelerated and coordinated policies, with collaboration among multiple areas of governments, regulators, companies, non-governmental organizations and patient groups. Public health has long been under-funded compared with the funding of other areas of health[145]. Long-term changes will necessitate investment in national and international digital centers of excellence, with the necessary balance of partners and pre-agreed access to digital datasets. A substantial investment in workforce education and skills is essential for growing digital public-health leadership[146].

Conclusion

The COVID-19 pandemic is ongoing, and it is too early to fully quantify the added value of digital technologies to the pandemic response. While digital technologies offer tools for supporting a pandemic response, they are not a silver bullet. The emerging consensus is that they have an important role in a comprehensive response to outbreaks and pandemics, complementing conventional public-health measures, and thereby contribute to reducing the human and economic impact of COVID-19. Cost-effectiveness and sustainability will require systems-level approaches to building digital online care pathways that link rapid and widespread testing with digital symptom checkers, contact tracing, epidemiological intelligence and long-term clinical follow up. The COVID-19 pandemic has confirmed not only the need for data sharing but also the need for rigorous evaluation and ethical frameworks with community participation to evolve alongside the emerging field of mobile and digital healthcare. Building public trust through strong communication strategies across all digital channels and demonstrating a commitment to proportionate privacy are imperative[147].

The future of public health is likely to be increasingly digital, and recognizing the importance of digital technology in this field and in pandemic preparedness planning has become urgent. Key stakeholders in the digital field, such as technology companies, should be long-term partners in preparedness rather than being partners only when emergencies are ongoing. Viruses know no borders and, increasingly, neither do digital technologies and data. There is an urgent need for alignment of international strategies for the regulation, evaluation and use of digital technologies to strengthen pandemic management and future preparedness for COVID-19 and other infectious diseases.

Received: 7 April 2020; Accepted: 2 July 2020;

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Competing interests

A.M.J., I.J.C., V.C.E., B.S.M., E.M.M., D.P., M.M.S., N.K. and R.A.M. received funding from the EPSRC for i-sense IRC in Agile Early Warning Sensing Systems for Infectious Diseases and AMR (EP/R00529X/1), and collaborate with Google, Microsoft and Telefonica, as well as diagnostic companies. N.K., R.A.M. and M.M.S. received funding from IRC Next Steps Plus: Ultra-Sensitive Enhanced NanoSensing of Anti-Microbial Resistance (u-sense, EP/R018391/1). A.M.J. received funding from NIHR. G.R. undertakes paid consultancy work for Google Health, and undertakes research on predictive analytics in brain imaging funded by the Wellcome Trust. M.M.S. is a consultant for 30T/Edixomed, Simmons and Simmons and Origin Sciences, and receives research grant funding from CRUK, The Wellcome Trust, EPSRC/MRC/UKRI, H2020 and ERC, as well as other grants.

Additional information

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