Wearable Contact Tracing

Key considerations and recommendations for public health officials in developing wearable contact tracing solutions during COVID-19

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31 July 2020

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IDRC | CRDI

International Development Research Centre
Centre de recherches pour le développement international

Canada

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Summary of the Problem

App-based contact tracing solutions have become popular during COVID-19. However, most such apps have seen mixed results with limited citizen uptake and numerous privacy and ethical concerns. Wearable contact tracing devices, which promise several improvements over app-based solutions, have met with considerable interest in recent times. This document explores the key considerations in developing and deploying wearable contact tracing devices and provides recommendations to decision makers.

Executive Summary

Contact tracing is a key public health intervention aimed at curtailing the spread of an infectious pathogen during a pandemic by identifying and isolating people who may have come into close contact with an infected individual. Since manual contact tracing has been shown to be too slow to curtail the spread of the virus, the COVID-19 pandemic has seen several digital contact tracing solutions proposed.

Both smartphones and dedicated devices can aid the function of contact tracing. The solutions currently available differ from each other in a few important ways based on the adopted technology, approach to data storage, and the usage of collected data. While tracing systems which store a person's location data in a central database provide public health authorities with more sources of information, they can lead to significant privacy compromises which can result in social stigma towards diagnosed carriers and local businesses; spread of misinformation and panic; and fraud and abuse by bad actors.

Wearable contact tracing offers several improvements over app-based contact tracing. They increase coverage by reaching people without smartphones, overcome several practical issues of smartphone apps, prevent the fusion of data from multiple sources (unlike smartphones), and give the user greater control over the data collected. However, the associated costs of manufacturing and the limited popularity of a new tracking device are potential limitations. Singapore has already piloted a TraceTogether token and several other solutions are either in development or ready to deploy.

Given the limited evidence on best practices around developing digital contact tracing, any wearable contact tracing solution should rely on the best available research, guided by public health objectives. Once deployed, their performance needs to be carefully and continuously evaluated on technological, public health, ethical, and legal dimensions to ensure that the intended public health benefits are met.

In order to maximize the public health benefits of wearable contact tracing while respecting other values, the following measures are recommended: (1) establish an expert working group; (2) deploy gradually with continuous monitoring to inform policy and practice; (3) default to voluntary use; (4) educate and engage with the public; (5) institute independence governance and oversight.

Contributors

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Unresolved Issues

This policy brief will be updated as necessary.

1. Introduction

Contact tracing is a key non-pharmaceutical intervention designed to curtail the spread of an infectious pathogen during a pandemic by breaking chains of transmission. It is deemed most effective as one piece of a three-part public health strategy where testing finds new cases, contact tracing identifies those who may have been exposed to the virus, and isolation prevents the potentially infected from transmitting the infection further (Salathé et al., 2020). Contact tracing can also reveal hotspots of transmission (locations, events, age groups, professions, etc.) which allow targeting of additional interventions for disease control. It is a process typically conducted by trained personnel, who, having identified an infected individual, trace and record their contact history, reach out to the potentially exposed, monitor them over time, and, where necessary, communicate with other contact tracers across geographical areas securely and confidentially.

The Need for Digital Contact Tracing

While classic contact tracing is known to be effective in slowing down the spread of infectious diseases (Klinkenberg, Fraser, & Heesterbeek, 2006), the latest biological research points to two characteristics of the SARS-CoV-2 virus which indicate that classic person-based contact tracing might not be sufficient for the effective control of the virus.

1. **Multiple modes of transmission during a long infectious period.** The infectious period for SARS-CoV-2 has been found to be 1-3 days before the onset of COVID-19 symptoms and can go on upto 10-14 days after (World Health Organization, 2020a). According to studies conducted thus far, it is primarily transmitted from infected people to others who are in close contact through respiratory droplets, by direct contact with infected persons, or by contact with contaminated objects and surfaces (World Health Organization, 2020b).
2. **Pre-symptomatic and asymptomatic transmission.** SARS-CoV-2 can be transmitted before the onset of COVID-19 symptoms (pre-symptomatic), or by those who don't exhibit symptoms at all (asymptomatic). Most people with SARS-CoV-2 are expected to develop symptomatic COVID-19, but a proportion will remain asymptomatic throughout their infection. Together, pre-symptomatic and asymptomatic transmission are estimated to account for 40-60% of all SARS-CoV-2 (Ferretti et al., 2020). Therefore, a substantial fraction of the overall transmission is missed if only symptomatic cases are detected and isolated.

The diversity of transmission modes during a long incubation period, coupled with asymptomatic and presymptomatic transmission, makes it challenging to identify all cases of COVID-19 through manual tracing. A group of researchers from the University of Oxford has argued, through an epidemiological modeling study, that classic contact tracing is not fast enough to prevent SARS-CoV-2 transmission, and digital solutions which can augment traditional contact tracing will be required. (Ferretti et al., 2020).

2. Different Approaches to Digital Contact Tracing

Many countries have already made digital contact tracing a part of their COVID-19 playbook. The first wave of these solutions was seen in China and South Korea, where contact tracers used a range of data sources – including security camera footage, credit card records, and location data from vehicles and mobile phones – to speed up the identification of contacts (Sonn, 2020). This approach, which also involved mass-broadcasting of confirmed cases (South Korea's public health messages reportedly contained personal information of patients), was heavily criticized by technology experts and activists due to its potential for breach of privacy, the spread of misinformation, compromised data security, and abuse by bad actors. In countries where such invasive approaches are untenable, other solutions which adhere to more ethical principles have been since tested and implemented (Zastrow, 2020).

While smartphone-based applications have become the most popular approach to digital contact tracing, any device embedded with the requisite technology, and governed by a design protocol that meets public health needs, can function as a digital contact tracing device. The most fundamental differences between digital contact tracing solutions lie not at the level of the device type, but at the level of the governing protocol, with significant public health and ethical implications. The most consequential of these differences can be understood in terms of the adopted technology, approach to data storage, and the usage of collected data.

a. **Location-based vs Bluetooth-based contact tracing**
   Contact tracing devices that leverage location data (usually some combination of Wi-Fi, cell tower and GPS), create a log of time-stamped trails of a person's movement. Upon the notification of a positive diagnosis of COVID-19 or potential exposure to an infected person, those logs are compared with users who have shared the same location. While this method allows for reasonably accurate information about a person's mobility and location, it leads to increased privacy concerns. On the other hand, contact tracing using Bluetooth Low Energy (BLE), record close interactions between users carrying Bluetooth enabled devices. Since it only detects the proximity between users, no location data is needed. Of the solutions currently available, MIT Safe Paths is location-based, whereas TraceTogether by Singapore, has taken the Bluetooth-based route.
b. **Centralized vs decentralized contact tracing**
   Early during the pandemic, South Korea implemented a system called Safe Korea that collected GPS records, credit card transactions, and security camera footage of its citizens in a centralized database in order to enforce quarantine orders and track possible contacts (Kim, 2020). These centralized systems are designed to incorporate data from a variety of sources that can be integrated for maximal effectiveness. In contrast, many other solutions have opted for a decentralized approach, where proximity or location data remains within a user's phone. For example, within the Apple-Google exposure notification system, the proximity data is stored locally, and the close contacts of an infected person can be notified by the app without any human ever seeing the data ("Exposure Notifications: Helping fight COVID-19 - Google," 2020). Proponents of the 'centralized' model argue that it allows health authorities to use the database to quickly construct a view of the network of contacts, enabling further epidemiological insights such as clusters and superspreaders. However, this also means personal information of users will be easily revealed to bad actors if the database is hacked.
c. **Contact tracing vs exposure notification**
   There is a subtle but important distinction between "contact tracing" and "exposure notification". Apple-Google's exposure notification system only performs notifications to the immediate contacts of an infected person. It does not allow for contact tracing as typically understood by revealing all the contacts of an infected person to the health authorities. The significance of this distinction was further highlighted when the original "Privacy-Preserving Tracing Protocol," was later renamed to "Exposure Notification" in late April (Haskins, 2020). It was due to this incompatibility that the Singapore Health authorities decided against the Apple-Google Exposure Notification System in their pandemic response. Singapore's BlueTrace protocol, on the other

hand, allows the health authorities to learn all the contacts of an infected person and build a full contact "graph". In a nutshell, exposure notification alone cannot determine the causality of an infection, which is known to yield rich epidemiological insights.

3. Wearable Technology for Contact Tracing

Singapore was the first country to develop and successfully deploy a contact tracing app while addressing many of the early concerns raised by privacy experts (O'Neill, Ryan-Mosley, & Johnson, 2020). However, despite a 90% smartphone penetration rate, the app has been downloaded by less than 40% of Singaporeans (Government of Singapore, 2020), a far cry from the 75% adoption that Singapore's National Development Minister has said would be needed for it to have a substantial impact (Chong, 2020). Late June, it was reported that Singapore had started distributing Bluetooth-powered, wearable contact tracing devices to the elderly, as the first phase of a renewed effort to cover each of its 5.7 million residents with a contact tracing device. While TraceTogether mobile apps will continue to be used, this shift towards wearable devices highlights several limitations of app-based contact tracing that may be of significance to countries that are aiming to expand their contact tracing efforts through digital solutions.

3.1 The Landscape of Wearable Contact Tracing Solutions

Wearable contact tracing tokens are relatively new, with the only large-scale deployment thus far seen in Singapore. However, there are reports of several other projects in development. Given the experience of the logistics sector in developing tracking devices, it is conceivable that many more will follow, especially if the initial experiments prove successful.

3.1.1 TraceTogether Token

The TraceTogether token is a hardware implementation of the BlueTrace protocol developed by Singapore's Government Technology Agency (GovTech) for the TraceTogether mobile app (Cross, 2020). The tracing token is said to be small, lightweight, and easy to use with an estimated battery life of six to nine months. Each wearable device carries a unique, personalized QR code that is hashed together with the current time to create a unique id for exchanging signals with other devices close by, or with mobile phones running the TraceTogether app. The proximity data is encrypted and kept in the device for a maximum of 25 days. Since the device has no internet or cellular connectivity, encrypted data cannot be remotely extracted from a device. The device does not collect GPS data, and the download of Bluetooth proximity data of confirmed cases will only happen once the device is handed over to the authorities.

According to government reports, each of the first set of TraceTogether wearable devices had been commissioned at USD 15 per device. The development of the device has also seen some amendments to the BlueTrace protocol, which has given more flexibility to the designers in overcoming design challenges. To build trust around the new device and foster community engagement, the Singapore Government invited a panel of four experts to inspect one of the devices before it was launched. It has also revealed further plans to hold a large-scale hackathon to further improve the token ("Improving TraceTogether through community engagement," 2020). A detailed explainer on the rationale for Singapore's wearable token (Huang, 2020a) and a breakdown of the TraceTogether token hardware (Cross, 2020) can be found in two separate blog posts written by two of the experts summoned by GovTech.

3.1.2 The Simmel Project

"Simmel" is an ongoing project started by a group of independent experts in April 2020, in response to a request by the NLnet Foundation for a hardware design proposal for a wearable contact tracing device. It is a token solution quite similar to the TraceTogether Bluetooth token in its approach and its hardware (Cross 2020) and enables COVID-19 contact tracing while preserving user privacy. The contact tracing algorithm is built on CircuitPython, an open-source language, to encourage community participation. While it is not strictly guided by any protocol yet, the decentralized approach does not allow for data uploads or remote data extraction. The developers have made the design source of hardware and firmware available so that the device can be recycled, reused, or securely destroyed once the pandemic is over ("Simmel Project," 2020). The project Simmel initially explored two paths for its core technology: Bluetooth, since it is a proven technology with mature chipsets and technical protocols, and NUS (near-ultrasound), which is directional and does NOT penetrate walls, thereby avoiding the "too many false positives" problem of Bluetooth technology. However, it was recently confirmed that the physics of NUS was not conducive to reliable contact tracing due to too many false negatives (Huang, 2020b).

3.1.3 Other Wearable Contact Tracing Solutions

Apart from TraceTogether and Simmel, there have been other reports of contact tracing physical tokens currently in development. The European Institute of Innovation & Technology (EIT Digital) is reportedly investigating the use of physical tokens as an alternative to app-based contact tracing solutions (EIT, 2020). Meanwhile, the popular IoT and security startup Nodle, non-profit foundation Coalition Network, and leading global technology solutions company Avnet, have announced a new smart wearable contact tracing device called the Nodle M1 (Nodle, 2020). In Singapore, Surbana Jurong, a government-owned infrastructure and development company, is reportedly trialing another contact tracing device and digital check-in system for Singapore to minimize infection spread at their worksites. This device is meant to complement, rather than replace, the existing TraceTogether token and the mobile app (Tham, 2020).

3.2 Why Use Wearable Devices Over Smartphone Apps?

The current state of technology allows for the manufacturing of robust, cheap, wearable tokens that consume little energy. Physical tokens, in fact, are quite popular in the logistics industry with established players and well-linked supply chains. Wearable tokens have several advantages over mobile apps for contact tracing.

a. **Smartphone penetration is quite low, especially in the Global South**

   For an app-based digital contact tracing solution to be effective, enough people need to download and use it. While there's no consensus around an exact figure, it is generally agreed that app-based digital contact tracing solutions require at least half the population to be using the app for them to have a significant impact. Most countries in the Global South have smartphone penetration rates far below 50%. For example, LIRNEasia's AfterAccess data reveals that smartphone ownership among the 15-65 aged populations in India, Pakistan, and Sri Lanka are at 17%, 13%, and 37%, respectively (LIRNEasia, 2019). Since the smartphone usage rates are known to be even lower among underprivileged populations who are more vulnerable to the pandemic, app-based solutions alone aren't likely to yield the full intended public health benefits of contact tracing.

b. Tokens overcome many of the issues experienced by mobile apps during implementation
Despite offering a lot of promise at the conceptual level, many contact tracing apps have run into practical issues during rollout. In Singapore, both Android and iOS operating systems reportedly posed problems in trying to use Bluetooth in the background, requiring the app to be active in the foreground to be useful. Some mobile apps are also not useful for those without compatible modern smartphones (Cross, 2020). There's also the very practical issue of phones running out of battery or people shutting down applications to preserve battery power during the day.

c. No sensor-fusion allows for strong isolation of user data
Being purpose-built for contact tracing, wearable tokens don't need additional sensors included in them. This strongly limits its ability to perform "sensor fusion" with a smartphone-like sensor suite consisting of Wi-Fi, GPS, and cell tower. By eliminating sensor-fusion, there is no risk of any geolocation data being leaked. It also makes it harder to make metadata-based attacks against user privacy.

d. Citizens have greater control over their contact history
Assuming that a remote data reading mechanism is not built into the device, citizens can be given a lot of control and confidence over their contact history data. Users are the physical keeper of their contact data with no third-party servers involved, until they volunteer to share their data with the authorities once diagnosed with the disease by surrendering the physical token. This means, in an extreme case, a user has the option of physically destroying their token to erase their history.

3.3 Potential Limitations of Wearable Contact Tracing Devices

While wearable contact tracing offers several advantages over app-based solutions, there are a few potential limitations. In countries with underdeveloped electronics manufacturing sectors, the associated development and production costs could prove to be prohibitive. Moreover, unlike a mobile phone, which people are incentivized to carry around with them regularly, the behavioral response to a visible wearable device is hard to foresee. The absence of a user-interface (due to cost considerations) might also add to the skepticism within people towards a new tracking device.

4. Going Forward: Challenges and Considerations

Just like mobile apps, wearable contact tracing devices will also work best in tandem with other public health measures in fighting the virus. Given the known limitations of the technologies involved, and the scant evidence of the effectiveness of any digital solution, wearable tokens need to be carefully and continuously evaluated on technological, public health, ethical and legal dimensions to ensure that the intended public health benefits are met.

a. Technological
The development of a contact tracing device will involve a series of design choices involving, among others, storage, processing capability, security, energy consumption, interface design, and cost. However, given the absence of established standards, these decisions will need to be made based on the best available knowledge guided by public health objectives. For example, while Bluetooth Low Energy (BLE) technology has been widely used for contact tracing tokens and app-based solutions, it has also been hampered by a large number of false positive and false negative cases (Cellan-Jones & Kelion, 2020). Other technologies such as Ultra Wide-Band have been

proposed as possible alternatives, but more testing is needed before they can become a part of contact tracing. It is essential to view the development of digital contact tracing as a dynamic process whereby the design is continuously improved through knowledge gained from the latest research and lessons learned from initial deployment.

b. Public health

Since wearable contact tracing, in principle, can accommodate most available technologies, public health officials must determine the type of data needed and the maximum permissible error rate. These decisions need to be informed by the capacity of the health system and the identified priorities of the pandemic response plan. Further, any digital contact tracing solution, including wearables, should complement existing contact tracing efforts and be seamlessly integrated into the ongoing processes. The health authorities should also consider the publication of de-identified data collected from wearable devices to support population-level epidemiological analysis.

c. Ethical

Given the amount of uncertainty and the limited success of digital contact tracing solutions deployed thus far, a foundational ethical consideration regarding the introduction of a new wearable token is whether such a device is justified in the first place. However, as the scientific understanding of the pandemic and ways to combat it evolve, new interventions will need to be trialed continuously. The success of such interventions will depend largely on the willingness of the public to trust the authorities and adopt any measures introduced. Transparency throughout the development process, regular and clear communication, expert and civic engagement, and proper governance and oversight can take a long way in building this trust. Further, given the disproportionate burden that the pandemic places on disadvantaged populations, any technological solution should be deployed to make sure the risks and the benefits of a new contact tracing device are distributed fairly and equitably (Kahn & Technologies, 2020).

d. Legal

Any careful consideration of legal implications of wearable contact tracing devices requires an examination of relevant laws and regulations of a given country. However, most legal issues around digital contact tracing solutions arise from the collection of personally identifiable information (PII) and the potential for their unauthorized or improper use. As highlighted by a recent report by Johns Hopkins University, the key considerations regarding the collection and usage of PII include: what type of data is collected; how the data are used and who may access them; how user consent is obtained; whether the entity collecting and using the data is the government or a private corporation; the context in which data are collected (e.g., employment, education, or commercial); and which governing bodies have jurisdiction over the program (Kahn & Technologies, 2020). As a general approach, it is always advisable to collect the minimum necessary amount of data, have privacy built into the device by design, and obtain freely given user content that reflects a full understanding of the terms for use.

5. Recommendations for Developing and Deploying Wearable Contact Tracing Devices

a. Establish an expert working group

Given the complexity and the urgency of the task of developing a contact tracing solution, the formulation of an expert working group is recommended, consisting of, but not limited to, scientists, tech experts, entrepreneurs, industrial manufacturers, public health officials, legal experts, and civil society representatives. The multi-domain experience and expertise would accelerate the development, foster coordination, and help avert certain pitfalls that might come with the prompt deployment of a novel device.

b. Deploy gradually with continuous monitoring to inform policy and practice

Despite the widespread coverage by the media, digital contact tracing solutions have, thus far, seen mixed results at best. Further, smartphone-based solutions, by definition, are unable to fully serve those who do not own a smartphone. Therefore, it is recommended that any deployment of wearable contact tracing devices be done gradually with the most vulnerable groups receiving immediate attention. Quick, but gradual rollout will allow the public health authorities to collect rapid feedback and evidence on the performance, benefits, and harms of the implemented technology. This information, coupled with evidence gathered from other contexts about competing technologies, will inform both subsequent iterations of the technological solutions and the policies that are governing them.

c. Default to voluntary use

Public health emergencies sometimes require temporary infringements on people's rights. However, such restrictions are justified only when there is a reasonable expectation of tangible health care benefits. Digital contact tracing, including wearable devices, are novel methods that have limited, if any evidence, of their effectiveness and the risks they may carry in terms of privacy, data security, and other potential misdeeds by bad actors. While access to wearable tokens should be made available to those who need it, it is recommended that an opt-in approach with clear and simple instructions on terms and operation be the standard. It is also generally believed that the voluntary use of new technology can enhance public acceptance and trust. However, the feasibility and value of opt-out approaches should also continue to be evaluated, assessing how different methods are likely to lead to different public health outcomes.

d. Educate and engage with the public

During the immediate aftermath of the COVID-19 outbreak, many countries had to announce overly restrictive control measures without consulting the public. However, as the battle against the pandemic continues to be waged over the long term, such approaches are unlikely to inspire trust and confidence in people. Instead, governments must make sure that the public has a reasonable understanding of the measures being taken, some say in how this is going to be done, or, at least, an assurance that their concerns will be addressed. Engaging with the public, therefore, should become a regular and ongoing activity. Authorities can also create specific opportunities for experts and civil society to weigh in at different stages of the development of the wearable device. Constant engagement and education will also help governments to stave off bad actors who try to confuse the public and create distrust in the institutions by spreading misinformation.

e. Institute independent governance and oversight

Effective governance of digital contact tracing systems requires transparency and mechanisms to ensure public well-being. Therefore, it is recommended that an independent governing body be formulated with the requisite expertise to review and monitor the development and deployment of wearable contact tracing devices. This governance body can address a range of topics, including the efficacy and the performance of the system; data security; ethical and regulatory implications; and the effects of digital control solutions beyond the COVID-19 pandemic.

References

Cellan-Jones, R., & Kelion, L. (2020, July 22). Coronavirus: The great contact-tracing apps mystery - BBC News. Retrieved July 28, 2020, from BBC News website: https://www.bbc.com/news/technology-53485569

Chong, C. (2020, April 1). About 1 million people have downloaded TraceTogether app, but more need to do so for it to be effective: Lawrence Wong, Singapore News & Top Stories - The Straits Times. Retrieved July 31, 2020, from Strait Times website: https://www.straitstimes.com/singapore/about-one-million-people-have-downloaded-the-tracetogether-app-but-more-need-to-do-so-for

Cross, S. X. (2020, June 21). Trace Together Token: Teardown and Design Overview. Retrieved July 24, 2020, from Xobs' Blog website: https://xobs.io/trace-together-token-teardown/

EIT. (2020, May 14). ANONYMOUS COVID-19 CONTACT TRACING USING PHYSICAL TOKENS | European Institute of Innovation & Technology (EIT). Retrieved July 28, 2020, from European Institute of Innovation and Technology website: https://eit.europa.eu/news-events/news/anonymous-covid-19-contact-tracing-using-physical-tokens

Exposure Notifications: Helping fight COVID-19 - Google. (2020). Retrieved July 28, 2020, from Google website: https://www.google.com/covid19/exposurenotifications/

Ferretti, L., Wymant, C., Kendall, M., Zhao, L., Nurtay, A., Abeler-Dörner, L., … Fraser, C. (2020). Quantifying SARS-CoV-2 transmission suggests epidemic control with digital contact tracing. *Science*, *368*(6491). https://doi.org/10.1126/science.abb6936

Government of Singapore, Smart Nation | Press Releases - Factsheet: TraceTogether Programme. (2020, June 8). Retrieved July 28, 2020, from Smart Nation Singapore website: https://www.smartnation.gov.sg/whats-new/press-releases/factsheet--tracetogether-programme

Haskins, C. (2020, May 20). Why Coronavirus Exposure Notifications And Contact Tracing Are Very Different Things. Retrieved July 28, 2020, from BuzzFeed News website: https://www.buzzfeednews.com/article/carolinehaskins1/what-are-exposure-notifications-contact-tracing-how-are

Huang, A. (2020a, June 23). On Contact Tracing and Hardware Tokens. Retrieved July 24, 2020, from bunnie:studio website: https://www.bunniestudios.com/blog/?p=5820

Huang, A. (2020b, July 7). A Near-Ultrasound (NUS) Data Link. Retrieved July 24, 2020, from bunnie:studios website: https://www.bunniestudios.com/blog/?p=5847

Improving TraceTogether through community engagement. (2020, July 6). Retrieved July 24, 2020, from GoveTech, Singapore website: https://www.tech.gov.sg/media/technews/2020-07-06-tracetogether-token-teardown

Kahn, J., & Technologies, J.P.E.G.D.C.T. (2020). Digital Contact Tracing for Pandemic Response: Ethics and Governance Guidance. In *Digital Contact Tracing for Pandemic Response*. https://doi.org/10.1353/book.75831

Kim, M. S. (2020, March 6). South Korea is watching quarantined citizens with a smartphone app | MIT Technology Review. Retrieved July 24, 2020, from MIT Technology Review website: https://www.technologyreview.com/2020/03/06/905459/coronavirus-south-korea-smartphone-app-quarantine/

Klinkenberg, D., Fraser, C., & Heesterbeek, H. (2006). The effectiveness of contact tracing in emerging epidemics. *PLoS ONE*, *1*(1). https://doi.org/10.1371/journal.pone.0000012

LIRNEasia. (2019). *AfterAccess: ICT access and use in Asia and the Global South*. Retrieved from https://lirneasia.net/2019/05/afteraccess-asia-report3/

Nodle. (2020, July 10). The Nodle M1 Wins "Enterprise Wearable Device of the Year" | by Nodle Team | Jul, 2020 | Medium. Retrieved July 28, 2020, from https://medium.com/@nodle/the-nodle-m1-wins-enterprise-wearable-device-of-the-year-8b420d9bdb3e

O'Neill, P. H., Ryan-Mosley, T., & Johnson, B. (2020, May 7). A flood of coronavirus apps are tracking us. Now it's time to keep track of them. | MIT Technology Review. Retrieved July 31, 2020, from MIT Technology Review website: https://www.technologyreview.com/2020/05/07/1000961/launching-mittr-covid-tracing-tracker/

Salathé M, Althaus CL, Neher R, et al. COVID-19 epidemic in Switzerland: on the importance of testing, contact tracing and isolation. Swiss Medical Weekly. 2020 Mar;150:w20225. DOI: 10.4414/smw.2020.20225

Simmel | Simmel Project. (2020). Retrieved July 28, 2020, from https://simmel.betrusted.io/

Sonn, J. W. (2020, March 20). Coronavirus: South Korea's success in controlling disease is due to its acceptance of surveillance. Retrieved July 28, 2020, from The Conversation website: https://theconversation.com/coronavirus-south-koreas-success-in-controlling-disease-is-due-to-its-acceptance-of-surveillance-134068

Tham, I. (2020, July 17). Coronavirus: New contact tracing device and check-in system on trial at worksite, Singapore News & Top Stories - The Straits Times. Retrieved July 24, 2020, from Straits Times website: https://www.straitstimes.com/singapore/new-contact-tracing-device-and-check-in-system-on-trial-at-worksite

World Health Organization. (2020a). Criteria for releasing COVID-19 patients from isolation. In *World Health Organization Scientific Brief*. Retrieved from https://www.who.int/publications/i/item/criteria-for-releasing-covid-19-patients-from-isolation

World Health Organization. (2020b). *Transmission of SARS-CoV-2: implications for infection prevention precautions*. Retrieved from https://www.who.int/publications/i/item/modes-of-transmission-of-virus-causing-covid-19-implications-for-ipc-precaution-recommendations

Zastrow, M. (2020). Coronavirus contact-tracing apps: can they slow the spread of COVID-19? *Nature*. https://doi.org/10.1038/d41586-020-01514-2