Spring 2022

Contact Tracing in the Era of Covid-19: Implementation of Traditional Strategies in Novel Contexts and Innovative Approaches to Address Existing Barriers

Tyler James Shelby
Yale University Graduate School of Arts and Sciences, tyler.j.shelby@gmail.com

## Abstract

Contact Tracing in the Era of COVID-19: Implementation of Traditional Strategies in New Contexts and Innovative Approaches to Address Existing Barriers

Tyler James Shelby

2022

Background: Contact tracing is an evidence-based intervention that became a core component of many COVID-19 response plans throughout the globe. Despite its demonstrated success within other disease contexts, early studies of COVID-19 contact tracing have reported mixed results regarding the effectiveness and impact of contact tracing on ultimate pandemic objectives such as case incidence or mortality. Yet, there remains a knowledge gap regarding contextual factors that influence implementation outcomes of contact tracing that may in turn influence its ultimate impact. The primary objective of this dissertation is to address this knowledge deficit by evaluating an emergency contact tracing program developed at the onset of the pandemic and evaluating the performance of various Bluetooth-assisted contact tracing technologies.

Methods: The emergency contact tracing program evaluated throughout this dissertation was established in partnership between the New Haven Health Department and Yale School of Public Health in March, 2020. In Aim 1 (Chapter 2), I evaluate implementation outcomes including *reach* (proportion of cases and contacts interviewed), *timeliness* (time from case testing to subsequent contact tracing steps), and sustainability of volunteer workforces. Within this Aim, I use quantitative methods including descriptive cascades to identify common reasons for case and contact drop-out, descriptive time measurements to evaluate timeliness of cumulative and individual contact tracing steps, and multilevel regression analyses to evaluate factors associated with successfully reaching cases and contacts. In Aim 2, I first use focus groups with contact tracers (Chapter 3) to qualitatively explore contextual elements associated with successful delivery of contact tracing. I use thematic analysis to analyze transcripts and the RE-AIM implementation science framework to organize the identified themes. In the second half of Aim 2 (Chapter 4), I draw on interviews with COVID-19 cases and contacts to qualitatively explore elements that influence behaviors upon which the uptake of contact tracing relies. These behaviors include testing, answering phone calls, participating in interviews, and isolating/quarantining. I thematically analyze transcripts and use the COM-B model of behavior change to organize the findings. In Aim 3 (Chapter 5), I evaluate two Bluetooth technologies used in a contact tracing pilot on a university campus. The first technology is an app-based approach, while the second uses a small, portable device to record Bluetooth data. I measure the sensitivity and specificity of each technology by comparing Bluetooth contact records to daily self-report records. I then use a post-participation survey to quantitatively and qualitatively evaluate the experiences of technology users and explore their perspectives.

Results: Of the 1,705 cases reported in Aim 1, 545 (32%) were not reached due to missing key information, and another 334 (20%) were not reached due to their declining

the calls or interview invitations. Ultimately, only 826 (48%) were interviewed. Of the 2,437 contacts reported by interviewed cases, 1,597 (66%) were not reached due to missing information, and another 153 (6%) were not reached due to their declining calls or interview invitations. Ultimately, only 687 (28%) were notified of their exposure. Median time to case interview from testing was five days and time to contact notification was 8 days. Various individual-, program-, and case-cluster factors were associated with successful outreach. Support from public health nurses was needed to stabilize the emergency contact tracing workforce due to surging caseloads and limited sustainability of volunteers (median time from sign-up to retirement from program was four weeks).

In Aim 2, contact tracers identified many challenges and successes of the program's implementation and made recommendations for improvement. Successfully engaging cases and contacts (the group hereafter referred to as "clients") appeared dependent on outreach preferences, tracer communication skills, and sources of community mistrust. Effectiveness of contact tracing appeared threatened by time delays and the difficulties of isolation and quarantine. Adoption of a volunteer workforce appeared to rely on volunteer motivations, collaborative training, and supervision. Last, implementation efficiency was influenced by available tools and coordination with other agencies, and program maintenance was threatened by the low sustainability of volunteer workforces. Interviews with clients shed light on additional elements influencing specific behaviors required in successful contact tracing, and these findings were categorized within the Capability, Opportunity, Motivation, Behavior (COM-B) Model. *Capability* of clients to engage in tracing efforts was influenced by COVID-19 symptoms or baseline knowledge.

Opportunities for engagement were influenced by structural and contextual resources and ties within social networks. Last, *Motivation* to engage in tracing efforts was influenced by symptoms, beliefs about deliverables and consequences of participating, trust in the health system, and emotional reactions of clients.

In Aim 3, the portable device had higher sensitivity (94% vs 57%; $p<.001$) and specificity (95% vs 87%; $p=.02$) compared to the app-only technology. Participants largely considered Bluetooth contact tracing to be appropriate on a university campus but felt less comfortable with using GPS or Wi-Fi technologies. Most preferred technology that was developed and managed by the university compared to a third party, and privacy concerns were common.

Conclusions: This dissertation presents some of the earliest efforts to better understand the contextual factors influencing success of COVID-19 contact tracing implementation, and its use of multiple and mixed methods to explore the implementation of contact tracing allows for the triangulation of findings from each individual Aim. Lacking information required for outreach posed a major barrier to reaching cases and contacts, although individual, case-cluster, and program-level factors associated with implementation success were also noted. While volunteers appeared to be an appropriate solution to emergency workforce needs, sustainability poses a significant threat to volunteer-driven programs as demonstrated quantitatively and qualitatively. Focus group and interview participants identified many individual-, program- and systems-level contextual elements influencing contact tracing delivery and uptake. Potential solutions to barriers as well as potential intervention activities to implement are discussed within these chapters. Last, Bluetooth technologies offer promising solutions to some contact tracing barriers, but the preferences of potential technology users and feasibility of managing such hardware/software approaches will be critical for uptake and adherence.

Contact Tracing in the Era of COVID-19: Implementation of Traditional Strategies in Novel Contexts and Innovative Approaches to Address Existing Barriers

A Dissertation
Presented to the Faculty of the Graduate School
Of
Yale University
In Candidacy for the Degree of
Doctor of Philosophy

By
Tyler James Shelby

Dissertation Director: Lucian Davis, MD, MAS

May, 2022

Table of Contents

Acknowledgements

What a jolly time this has been, some of the time. And what a rush it was, the rest. There are many names, some of which I've forgotten, belonging to those that have contributed in big ways and small ways to guiding, energizing, supporting, entertaining, and caring for me along the way. To each of you, I extend my gratitude.

To Dr. Luke Davis, for your thoughtfulness, passion, and never-ending optimism. In a world filled with objectives, deadlines, and metrics, your dedication to kindness does not go unnoticed. Thank you for sharing your expertise, for guiding me through this chapter of my life, and for always taking the time to care - it has truly been a pleasure to work with and learn from you.

To Dr. Lauretta Grau, for your eagerness to learn about others and for your willingness to share your experiences and perspective. Also, for your humor. Especially for your humor. Your contributions to my training have been immense, and your good spirits have kept me lighthearted along the way.

To Dr. Linda Niccolai, for your leadership, endurance, and strength in an environment that was rapidly changing in every possible way. Thank you for opening the many doors that made this dissertation possible, and for trusting me to walk through them with you.

To Dr. Laura Forastiere, for your creativity and willingness to collaborate and learn together. You inspire me to continue learning about the ways in which human interactions shape the world around us, and for that I thank you.

To the New Haven Health Department and the many public health partners that truly gave their all to keep the COVID-19 pandemic at bay. To Director Maritza Bond, for her leadership, her partnership, and her willingness to sacrifice in the name of progress and community. To Brian Weeks, for his good humor, kind heart, and seemingly endless energy. I thank each of you, and the rest of our public partners, for your contributions to making the world a better place.

To the volunteer contact tracers, COVID-19 cases, and COVID-19 contacts who lent their experiences and perspective to this work. Without you, this would not have been possible. To the many other faculty, staff and students that shared their expertise, contributed their time and effort, and kept me company along the way - Dr Xin Zhou, Dr. Rajit Manohar, Amanda Gupta, Lizzie White, Rachel Hennein, Christopher Schenck, Justin Goodwin, and more.

To the Yale MD/PhD Program for supporting me and the many other students along the twists and turns of our training. To Drs. Barbara Kazmierczak, Michael Cappello, Tamar Taddei, and Fred Gorelick for their insight and advice throughout. To Cheryl DeFilippo, for always keeping her door ajar, for sharing her life's stories and lessons, and for watering my plants when they needed a caretaker. To Sue Sansone, for showing me kindness for kindness' sake, and for her wit and joyfulness. To Dr. Chris Tschudi and Melanie Elliot for keeping me on track at the School of Public Health, for helping me make the difficult decisions along the way, and for keeping me entertained in the meantime. Your care and support mean the world to your students.

To my dearest family. To my copilot, Sasha, for her love, silliness, and sense of adventure that keeps me bouncing on my feet. To my father, David, who inspires me to take life one day at a time, always with an appreciation for the opportunity to learn from those around me. To my mother, Kathy, who never ceases to ask how things are going,

even now as I write this, distracting me as only a caring and curious mother can. To Kassy, whose determination will allow her to overcome any obstacle. To Sidney, whose eyes see the world at its best, despite its worst. To Miah, whose spirited music and laughter I hear when I think of home. I simply couldn’t imagine or ask for better sisters. To my brother, who watched over me as a child, ran alongside me through the wilds of youth, and inspires me now with his curiosity and interest in the world around him. I love you all and thank you for your support and care throughout.

To my friends that have ceaselessly reminded me that life is best when in good company. To Jon, whose strength, humor, support, and feigned grumpiness are matched only by his love for circle-shaped foods. To Neil, who taught me to ski (and to fall safely!), and who always took the time to listen, care, and celebrate. To Jill for teaching me to play croquet, and for never missing an opportunity to bring out the hammers. To Elsie, for laughing, conspiring, and most importantly, for crasfting the cleverest of insults.

To the many others whose names I have not mentioned, but who still impacted me in immeasurable ways, I extend my profound gratitude. Thank you, thank you, thank you.

Chapter One. Introduction

1.1 The Role of Non-Pharmaceutical Interventions in Combatting COVID-19

Since its recent emergence, Coronavirus Disease 2019 (COVID-19) has been reported in nearly every country (1), resulted in hundreds of millions of cases and millions of deaths worldwide (1), and impacted the world's psychological and social wellbeing (2, 3), health systems (4, 5), and economies (6, 7) in myriad ways. As the world grapples with recurrent surges in case incidence, the emergence of viral variant strains, and ongoing vaccination campaigns, COVID-19 continues to impact the world and will for years to come. In light of this, learning from the initial stages of the pandemic and identifying mechanisms for improvement in response to such pandemic events is critical. Such efforts will not only sharpen our ongoing response to COVID-19 but also prepare us for the onset of future pandemics and epidemics. The opening chapter of any pandemic is especially fraught with challenges, and it is within that context that experience, prior knowledge, and preparedness are key. It is also within that context that this dissertation will focus.

During the COVID-19 pandemic's first year and prior to the development of the first COVID-19 vaccine, public health agencies around the globe heavily relied on non-pharmaceutical interventions (NPIs) (8, 9). These included testing (10, 11), contact tracing (12), physical distancing (13), mask mandates (14), bans on travel or public gatherings (15, 16), and lockdowns (17), among others. The initial lack of capacity for widespread testing programs (10 , 18) and undesirable economic impacts of lockdowns, however, placed additional pressure on contact tracing. Although it is a traditional intervention used in many other disease settings, the implementation of contact tracing in the novel context of COVID-19 was met with many barriers due to the scale of the pandemic and finite public health workforces and resources. Despite these obstacles, contact tracing became a principal component of many nations' responses to COVID-19, and remains central even in the pandemic's post-vaccine phase due to limited vaccine uptake and breakthrough transmission.

The primary goal of this dissertation is therefore to obtain a better understanding of the implementation context and challenges associated with COVID-19 contact tracing. I aim to accomplish this by presenting a multiple methods implementation evaluation of an emergency contact tracing program established in New Haven, CT at the onset of the pandemic, and by presenting a pilot study of Bluetooth-assisted contact tracing. First, though, I will briefly review the history of contact tracing in other disease contexts and the existing literature regarding COVID-19 contact tracing.

1.2 Contact tracing pre-COVID-19

Contact tracing is a complex intervention with many steps, including 1) identifying cases through testing, 2) reaching cases to discuss test results and provide isolation instructions if applicable, 3) eliciting data about exposed contacts from cases, and 4) reaching contacts to notify them of their exposure, provide instructions regarding quarantine if applicable, and link them to monitoring, testing, and/or vaccination if applicable. Tracing and quarantine have been used for hundreds of years in many contexts to reduce transmission of infectious diseases such as bubonic plague (19), cholera (19), smallpox (20), measles (21), influenza (22), Ebola (23), tuberculosis (TB) (24), HIV (25), and other sexually transmitted infections (STIs) (26). In addition to its effects on disease transmission, contact tracing has also been associated with improved treatment outcomes and lower mortality among index cases (27, 28), may provide additional opportunities to reduce mortality among contacts through earlier disease detection and treatment initiation (29), and also creates a window of interaction between the health system and contacts which may be used for additional health screening (30-32).

In practice, the implementation of contact tracing varies depending on the epidemiologic characteristics of the disease in question, as well as the context and resources at hand. For example, the reproductive number (R_0) estimates for TB range from below one to over four (33), dependent upon many factors including prevalence of active infection, individual respiratory rates, exposure length, degree of infectiousness, environmental airflow or ventilation rates, and immune status of susceptible individuals among others (34). Based on these factors, contact tracing for TB, alternatively called “contact investigation,” frequently focuses only on contacts exposed in high-exposure and low-airflow settings, such as households (24). Contact tracers often conduct home visits in coordination with the index case during which they screen household contacts for signs of TB and refer them for additional testing if applicable. Such home visits are frequently also used for HIV screening. While molecular and modelling evidence suggests that expanding TB contact tracing beyond households may increase yield of tracing (35-38), resource limitations often pose a challenge to this, and tracing is often limited to household screening, especially in low- and middle-income countries (24).

Contact tracing for STIs, on the other hand, utilizes a variety of different approaches to contacting, screening and/or treating exposed sexual contacts through what is more commonly called “partner notification” (26). In this context, index cases are often able to choose between notifying and referring their own contacts to a clinic (“patient referral”) or requesting to remain anonymous, in which scenarios care providers perform the outreach (“provider referral”) (26). In some settings, index cases may even be provided with antibiotics to deliver to their contacts, bypassing the interaction between the contact and care provider entirely. For HIV, contact tracing is often expanded to include testing of at-risk family members such as children, and these approaches have shown benefits not only in increasing diagnostic yield but also linkage to care (39-43).

While neither of the contact tracing versions above involve a typical quarantine period for contacts as we have seen implemented for COVID-19, contact tracing for previous SARS and MERS outbreaks consistently relied on quarantine and testing as the key end-point (44-47) for contacts. Such strategies are motivated by pathogen transmission dynamics that increase community spread, and the goal of this strategy is to prevent such broad transmission by reducing any and all exposure. In such settings where pathogen or environmental characteristics drive such an increase in transmission, the potential impact of contact tracing to reduce transmission and disease is similarly increased. However, as we have seen in COVID-19, there may be mitigation scenarios in which transmission rates are exceedingly high and community-wide lockdowns may be more feasible than tracing individual cases and contacts.

Despite its frequent use and well-documented impacts on infectious disease control, contact tracing has never been simple. Several challenges to contact tracing documented across different disease contexts prior to COVID-19 include difficulties recruiting and training contact tracing workforces (48-50); data management (49); mistrust and fears regarding invasion of privacy or manipulation and control of the public (47, 49, 51, 52); stigma (48, 53); limited access to clinics and providers (48, 51); gaps in community understanding of diseases or contact tracing's purpose and importance (52, 54); and case or contact inability to comply with instructions due to financial, nutritional, or social needs (48, 49). Acknowledging these challenges will help the reader interpret those found within the context of COVID-19.

1.3 Implementation of COVID-19 in the context of COVID-19

In response to the COVID-19 pandemic, countries around the globe devoted immense effort and resources towards rapid development of contact tracing programs (55-64). Implementation strategies varied greatly, however, evidenced by the various ways in which programs built their workforces or adapted and used technology. While some programs were able to hire contact tracing staff, many others recruited volunteers (55, 65), enlisted help from military service members (66), reassigned health workers to contact tracing or otherwise added contact tracing to their existing responsibilities (55, 67-69), or outsourced call efforts (70).

The use of technology to aid contact tracing similarly varied. Some exemplar nations such as Taiwan rapidly deployed and used national data management systems (60) featuring rapid and electronic integration of data from multiple sources to allow easier identification, monitoring and support of contacts. Alternatively, other nations including the US lacked such integrated systems and relied on outdated methods and technologies, including fax machines, to relay important and timely information such as test results (70). Technology wasn't only used for data management, however. Several nations led the world in implementing new data-gathering techniques to identify contacts, for example using Bluetooth applications (71), geo-location data (72), or credit/debit card transaction records (73). Such approaches were often met with skepticism (74), however, and incomplete uptake of the technology in many parts of the world ultimately limited the utility of these strategies (75, 76). While many have encouraged the use of such technology for contact tracing (77), it appears that such approaches will only support, and not replace, traditional contact tracing in most parts of the world due to skepticism and barriers to technology access (78).

A final point of varied implementation was the scope of contact tracing activities. Some programs went beyond routine contact tracing and implemented "backward" contact tracing in which they attempted to identify the source of an index case's infection (79), while others traced not only the index case's contacts, but the contacts of those contacts (80). Such expansive strategies are likely more applicable in settings of lower transmission, and less useful or feasible in mitigation phases when public health resources are exceedingly stressed.

Based on the varied approaches to COVID-19 contact tracing across the globe, it is difficult to measure and fully understand the impact of contact tracing on the COVID-19 pandemic. While some studies have shown associations between contact tracing and reduced mortality or case incidence (59, 81, 82), not all have (83). While there are limited studies evaluating the impact of contact tracing on ultimate pandemic outcomes, there are many more focusing on contact tracing process outcomes, such as yield (proportion of cases and contacts interviewed) and timeliness (time to interviews from symptoms onset, exposure, or identification), which can be compared against the benchmarks set forth by the CDC. Based on a suggested R_0 of 2.5 (84), these benchmarks suggest that contact tracers must reach 60% of cases and quarantine their contacts within six days of exposure. Such goals are hard to meet, however.

A recent study evaluating 14 contact tracing programs in the US (12) found that only 59% of total cases were reached for an interview, yet only 56% of the interviewed cases reported any contacts. In terms of timeliness, only 9 of the 14 sites had a median time from case sample collection to contact notification of six days or less. The study did not report time from contact exposure to notification, though, which would have likely been longer than six days assuming that some or most contact exposures occurred prior to the index case’s testing. Among the individual sites included in this study, as well as other programs evaluated elsewhere, success rates of reaching cases range from 33-100% (12, 85-87). Several studies also reported similar times to contact outreach as a median of six days starting from case symptom onset (85, 87). In addition to the difficulties meeting CDC benchmarks for yield and timeliness, several studies have also measured adherence to isolation and quarantine, reporting adherence as low as 25% (88-90). Survey data from some of these studies indicates that adherence may be influenced by several factors including perceptions of risk, age, socioeconomic status, work and family responsibilities, and observed/perceived behaviors of others (89, 90).

1.4 Research Contribution

Considering the findings above, it is clear that COVID-19 contact tracing faces challenges on many fronts. Nonetheless, the positive findings linking COVID-19 contact tracing to reduced mortality and case incidence, as well as contact tracing's efficiency in some contexts, are encouraging and indicate the potential impact of this intervention. Much remains unknown, however, about the implementation context and strategies that determine a program's effectiveness. This lack of clarity is driven by the varied implementation of contact tracing across settings, a general lack of reporting using standardized implementation science frameworks, and limited identification of mechanisms that drive success or failure. For example, of the many cited studies reporting percentages of cases reached above, only one directly reports reasons why unreached cases were not reached (e.g., invalid phone numbers, refusal to participate, etc.) (86) and only one compares case outcome differences across racial/ethnic groups (12). None use regression analyses to evaluate additional case, contact, or program characteristics associated with success, yet identifying determinants of case or contact drop-off is critical to identifying strategies for improvement. Furthermore, while many modelling studies have proposed the deployment of technology-assisted contact tracing (77) or predicted its impact (91), there are relatively few studies evaluating the effectiveness or performance metrics of the various technology platforms when used for contact tracing (91, 92). Such evaluations are necessary to inform public health guidance regarding implementation and adoption of these strategies.

This dissertation aims to address these knowledge gaps throughout the next five chapters. Chapters 2-4 present a multiple methods evaluation of a volunteer contact tracing program launched at the onset of the COVID-19 pandemic in New Haven, CT. In Chapter 2, I use descriptive cascades to measure yield and timeliness of the contact tracing program; hierarchical regression models to measure case, contact, or program-level factors associated with success; a longitudinal regression model and descriptive time measurements to evaluate volunteer workforce stability; and the implementation science RE-AIM framework (93) to synthesize these findings. In Chapter 3, I present qualitative findings from focus groups with contact tracing volunteers that identify barriers, facilitators, and potential solutions for contact tracing implementation. I use thematic analysis (94) to analyze the data and the RE-AIM framework to organize the identified themes. In Chapter 4, I present qualitative findings from interviews with cases and contacts that were called by the contact tracing program. This chapter focuses on identifying factors that influence case and contact engagement in key contact tracing behaviors including testing, answering phone calls, participating in contact tracing interviews, and isolating or quarantining. I use thematic analysis to analyze the data and the Capability, Opportunity, Motivation, Behavior (COM-B) Model (95) to organize the themes. In Chapter 5, I deviate from traditional contact tracing, and present a pilot evaluation of two Bluetooth-assisted contact tracing approaches developed at Yale University. This mixed methods pilot focuses on measuring performance metrics of the two technologies (sensitivity and specificity), assessing participant perceptions regarding appropriateness, usability, acceptability, and adherence via survey, and qualitatively exploring additional feedback provided by participants to triangulate our findings. In Chapter 6, I conclude by reviewing the major findings of the dissertation and looking forward to how they may be applied in the next phase of the pandemic and beyond.

1.5 References

1. WHO Coronavirus (COVID-19) Dashboard: World Health Orgainzation [cited 2021]. Available from: https://covid19.who.int/.
2. Dubey S, Biswas P, Ghosh R, Chatterjee S, Dubey MJ, Chatterjee S, et al. Psychosocial impact of COVID-19. Diabetes Metab Syndr. 2020;14(5):779-88.
3. Mazumder A, Bandhu Kalanidhi K, Sarkar S, Ranjan P, Sahu A, Kaur T, et al. Psycho-social and behavioural impact of COVID 19 on young adults: Qualitative research comprising focused group discussion and in-depth interviews. Diabetes Metab Syndr. 2021;15(1):309-12.
4. Blumenthal D, Fowler EJ, Abrams M, Collins SR. Covid-19 - Implications for the Health Care System. N Engl J Med. 2020;383(15):1483-8.
5. Baker DW. Trust in Health Care in the Time of COVID-19. JAMA. 2020;324(23):2373-5.
6. Barlow P, van Schalkwyk MC, McKee M, Labonte R, Stuckler D. COVID-19 and the collapse of global trade: building an effective public health response. Lancet Planet Health. 2021;5(2):e102-e7.
7. Verschuur J, Koks EE, Hall JW. Global economic impacts of COVID-19 lockdown measures stand out in high-frequency shipping data. PLoS One. 2021;16(4):e0248818.
8. Perra N. Non-pharmaceutical interventions during the COVID-19 pandemic: A review. Phys Rep. 2021;913:1-52.
9. Tabari P, Amini M, Moghadami M, Moosavi M. International Public Health Responses to COVID-19 Outbreak: A Rapid Review. Iran J Med Sci. 2020;45(3):157-69.
10. Mercer TR, Salit M. Testing at scale during the COVID-19 pandemic. Nature Reviews Genetics. 2021;22(7):415-26.
11. Tang S, Sanchez Perez M, Saavedra-Campos M, Paranthaman K, Myers R, Fok J, et al. Mass testing after a single suspected or confirmed case of COVID-19 in London care homes, April-May 2020: implications for policy and practice. Age Ageing. 2021;50(3):649-56.
12. Lash RR, Moonan PK, Byers BL, Bonacci RA, Bonner KE, Donahue M, et al. COVID-19 Case Investigation and Contact Tracing in the US, 2020. JAMA Network Open. 2021;4(6):e2115850-e.
13. Chu DK, Akl EA, Duda S, Solo K, Yaacoub S, Schunemann HJ, et al. Physical distancing, face masks, and eye protection to prevent person-to-person transmission of SARS-CoV-2 and COVID-19: a systematic review and meta-analysis. Lancet. 2020;395(10242):1973-87.
14. Guzman-Cottrill JA, Malani AN, Weber DJ, Babcock H, Haessler SD, Hayden MK, et al. Local, state and federal face mask mandates during the COVID-19 pandemic. Infect Control Hosp Epidemiol. 2021;42(4):455-6.
15. Costantino V, Heslop DJ, MacIntyre CR. The effectiveness of full and partial travel bans against COVID-19 spread in Australia for travellers from China during and after the epidemic peak in China. J Travel Med. 2020;27(5).
16. Ahmed QA, Memish ZA. The cancellation of mass gatherings (MGs)? Decision making in the time of COVID-19. Travel Med Infect Dis. 2020;34:101631.

17. Caristia S, Ferranti M, Skrami E, Raffetti E, Pierannunzio D, Palladino R, et al. Effect of national and local lockdowns on the control of COVID-19 pandemic: a rapid review. Epidemiol Prev. 2020;44(5-6 Suppl 2):60-8.
18. Mervosh S, Fernandez M. Months Into Virus Crisis, U.S. Cities Still Lack Testing Capacity: The New York Times; 2020. Available from: https://www.nytimes.com/2020/07/06/us/coronavirus-test-shortage.html.
19. Tognotti E. Lessons from the history of quarantine, from plague to influenza A. Emerg Infect Dis. 2013;19(2):254-9.
20. Lane JM. Mass vaccination and surveillance/containment in the eradication of smallpox. Curr Top Microbiol Immunol. 2006;304:17-29.
21. Thole S, Kalhoefer D, An der Heiden M, Nordmann D, Daniels-Haardt I, Jurke A. Contact tracing following measles exposure on three international flights, Germany, 2017. Euro Surveill. 2019;24(19).
22. Eames KT, Webb C, Thomas K, Smith J, Salmon R, Temple JM. Assessing the role of contact tracing in a suspected H7N2 influenza A outbreak in humans in Wales. BMC Infect Dis. 2010;10:141.
23. Faye O, Boelle PY, Heleze E, Faye O, Loucoubar C, Magassouba N, et al. Chains of transmission and control of Ebola virus disease in Conakry, Guinea, in 2014: an observational study. Lancet Infect Dis. 2015;15(3):320-6.
24. Fox GJ, Barry SE, Britton WJ, Marks GB. Contact investigation for tuberculosis: a systematic review and meta-analysis. Eur Respir J. 2013;41(1):140-56.
25. Brown LB, Miller WC, Kamanga G, Nyirenda N, Mmodzi P, Pettifor A, et al. HIV partner notification is effective and feasible in sub-Saharan Africa: opportunities for HIV treatment and prevention. J Acquir Immune Defic Syndr. 2011;56(5):437-42.
26. Ward H, Bell G. Partner notification. Medicine (Abingdon). 2014;42(6):314-7.
27. Baluku JB, Kabamooli RA, Kajumba N, Nabwana M, Kateete D, Kiguli S, et al. Contact tracing is associated with treatment success of index tuberculosis cases in Uganda. Int J Infect Dis. 2021;109:129-36.
28. Oliveira SP, Carvalho MDB, Pelloso SM, Caleffi-Ferracioli KR, Siqueira VLD, Scodro RBL, et al. Influence of the identification of contacts on the adherence of index tuberculosis cases to treatment in a high incidence country. Int J Infect Dis. 2017;65:57-62.
29. Group ISS, Lundgren JD, Babiker AG, Gordin F, Emery S, Grund B, et al. Initiation of Antiretroviral Therapy in Early Asymptomatic HIV Infection. N Engl J Med. 2015;373(9):795-807.
30. Zayar NN, Sangthong R, Saw S, Aung ST, Chongsuvivatwong V. Combined Tuberculosis and Diabetes Mellitus Screening and Assessment of Glycaemic Control among Household Contacts of Tuberculosis Patients in Yangon, Myanmar. Trop Med Infect Dis. 2020;5(3).
31. Stout JE, Katrak S, Goswami ND, Norton BL, Fortenberry ER, Foust E, et al. Integrated screening for tuberculosis and HIV in tuberculosis contact investigations: lessons learned in North Carolina. Public Health Rep. 2014;129 Suppl 1:21-5.
32. Ochom E, Meyer AJ, Armstrong-Hough M, Kizito S, Ayakaka I, Turimumahoro P, et al. Integrating home HIV counselling and testing into household TB contact investigation: a mixed-methods study. Public Health Action. 2018;8(2):72-8.

33. Ma Y, Horsburgh CR, White LF, Jenkins HE. Quantifying TB transmission: a systematic review of reproduction number and serial interval estimates for tuberculosis. Epidemiol Infect. 2018;146(12):1478-94.
34. Sze To GN, Chao CY. Review and comparison between the Wells-Riley and dose-response approaches to risk assessment of infectious respiratory diseases. Indoor Air. 2010;20(1):2-16.
35. Andrews JR, Morrow C, Walensky RP, Wood R. Integrating social contact and environmental data in evaluating tuberculosis transmission in a South African township. J Infect Dis. 2014;210(4):597-603.
36. Buu TN, van Soolingen D, Huyen MN, Lan NN, Quy HT, Tiemersma EW, et al. Tuberculosis acquired outside of households, rural Vietnam. Emerg Infect Dis. 2010;16(9):1466-8.
37. Glynn JR, Guerra-Assuncao JA, Houben RM, Sichali L, Mzembe T, Mwaungulu LK, et al. Whole Genome Sequencing Shows a Low Proportion of Tuberculosis Disease Is Attributable to Known Close Contacts in Rural Malawi. PLoS One. 2015;10(7):e0132840.
38. Johnstone-Robertson SP, Mark D, Morrow C, Middelkoop K, Chiswell M, Aquino LD, et al. Social mixing patterns within a South African township community: implications for respiratory disease transmission and control. Am J Epidemiol. 2011;174(11):1246-55.
39. Mahachi N, Muchedzi A, Tafuma TA, Mawora P, Kariuki L, Semo BW, et al. Sustained high HIV case-finding through index testing and partner notification services: experiences from three provinces in Zimbabwe. J Int AIDS Soc. 2019;22 Suppl 3:e25321.
40. Jubilee M, Park FJ, Chipango K, Pule K, Machinda A, Taruberekera N. HIV index testing to improve HIV positivity rate and linkage to care and treatment of sexual partners, adolescents and children of PLHIV in Lesotho. PLoS One. 2019;14(3):e0212762.
41. Kahabuka C, Plotkin M, Christensen A, Brown C, Njozi M, Kisendi R, et al. Addressing the First 90: A Highly Effective Partner Notification Approach Reaches Previously Undiagnosed Sexual Partners in Tanzania. AIDS Behav. 2017;21(8):2551-60.
42. Lewis Kulzer J, Penner JA, Marima R, Oyaro P, Oyanga AO, Shade SB, et al. Family model of HIV care and treatment: a retrospective study in Kenya. J Int AIDS Soc. 2012;15(1):8.
43. DeGennaro V, Zeitz P. Embracing a family-centred response to the HIV/AIDS epidemic for the elimination of pediatric AIDS. Glob Public Health. 2009;4(4):386-401.
44. Medicine Io. Learning from SARS: Preparing for the Next Disease Outbreak: Workshop Summary. Knobler S, Mahmoud A, Lemon S, Mack A, Sivitz L, Oberholtzer K, editors. Washington (DC)2004.
45. Ooi PL, Lim S, Chew SK. Use of quarantine in the control of SARS in Singapore. Am J Infect Control. 2005;33(5):252-7.
46. Kang M, Song T, Zhong H, Hou J, Wang J, Li J, et al. Contact Tracing for Imported Case of Middle East Respiratory Syndrome, China, 2015. Emerg Infect Dis. 2016;22(9):1644-6.
47. Lim PL. Middle East respiratory syndrome (MERS) in Asia: lessons gleaned from the South Korean outbreak. Trans R Soc Trop Med Hyg. 2015;109(9):541-2.

48. Tesfaye L, Lemu YK, Tareke KG, Chaka M, Feyissa GT. Exploration of barriers and facilitators to household contact tracing of index tuberculosis cases in Anlemo district, Hadiya zone, Southern Ethiopia: Qualitative study. PLoS One. 2020;15(5):e0233358.
49. Olu OO, Lamunu M, Nanyunja M, Dafae F, Samba T, Sempiira N, et al. Contact Tracing during an Outbreak of Ebola Virus Disease in the Western Area Districts of Sierra Leone: Lessons for Future Ebola Outbreak Response. Front Public Health. 2016;4:130.
50. Barker KM, Ling EJ, Fallah M, VanDeBogert B, Kodl Y, Macauley RJ, et al. Community engagement for health system resilience: evidence from Liberia's Ebola epidemic. Health Policy Plan. 2020;35(4):416-23.
51. Ayakaka I, Ackerman S, Ggita JM, Kajubi P, Dowdy D, Haberer JE, et al. Identifying barriers to and facilitators of tuberculosis contact investigation in Kampala, Uganda: a behavioral approach. Implement Sci. 2017;12(1):33.
52. Caleo G, Duncombe J, Jephcott F, Lokuge K, Mills C, Looijen E, et al. The factors affecting household transmission dynamics and community compliance with Ebola control measures: a mixed-methods study in a rural village in Sierra Leone. BMC Public Health. 2018;18(1):248.
53. Greiner AL, Angelo KM, McCollum AM, Mirkovic K, Arthur R, Angulo FJ. Addressing contact tracing challenges-critical to halting Ebola virus disease transmission. Int J Infect Dis. 2015;41:53-5.
54. Ilesanmi OS. Learning from the challenges of Ebola Virus Disease contact tracers in Sierra Leone, February, 2015. Pan Afr Med J. 2015;22 Suppl 1:21.
55. Nachega JB, Atteh R, Ihekweazu C, Sam-Agudu NA, Adejumo P, Nsanzimana S, et al. Contact Tracing and the COVID-19 Response in Africa: Best Practices, Key Challenges, and Lessons Learned from Nigeria, Rwanda, South Africa, and Uganda. Am J Trop Med Hyg. 2021.
56. Nachega JB, Grimwood A, Mahomed H, Fatti G, Preiser W, Kallay O, et al. From Easing Lockdowns to Scaling-Up Community-Based COVID-19 Screening, Testing, and Contact Tracing in Africa - Shared Approaches, Innovations, and Challenges to Minimize Morbidity and Mortality. Clin Infect Dis. 2020.
57. Lee SW, Yuh WT, Yang JM, Cho YS, Yoo IK, Koh HY, et al. Nationwide Results of COVID-19 Contact Tracing in South Korea: Individual Participant Data From an Epidemiological Survey. JMIR Med Inform. 2020;8(8):e20992.
58. Valent F, Gallo T, Mazzolini E, Pipan C, Sartor A, Merelli M, et al. A cluster of COVID-19 cases in a small Italian town: a successful example of contact tracing and swab collection. Clin Microbiol Infect. 2020;26(8):1112-4.
59. Vecino-Ortiz AI, Villanueva Congote J, Zapata Bedoya S, Cucunuba ZM. Impact of contact tracing on COVID-19 mortality: An impact evaluation using surveillance data from Colombia. PLoS One. 2021;16(3):e0246987.
60. Jian SW, Cheng HY, Huang XT, Liu DP. Contact tracing with digital assistance in Taiwan's COVID-19 outbreak response. Int J Infect Dis. 2020;101:348-52.
61. Draper AD, Dempsey KE, Boyd RH, Childs EM, Black HM, Francis LA, et al. The first 2 months of COVID-19 contact tracing in the Northern Territory of Australia, March-April 2020. Commun Dis Intell (2018). 2020;44.

62. Spencer KD, Chung CL, Stargel A, Shultz A, Thorpe PG, Carter MW, et al. COVID-19 Case Investigation and Contact Tracing Efforts from Health Departments - United States, June 25-July 24, 2020. MMWR Morb Mortal Wkly Rep. 2021;70(3):83-7.
63. O'Dowd A. Covid-19: UK test and trace system still missing 80% target for reaching contacts. BMJ. 2020;370:m2875.
64. Lai SHS, Tang CQY, Kurup A, Thevendran G. The experience of contact tracing in Singapore in the control of COVID-19: highlighting the use of digital technology. Int Orthop. 2021;45(1):65-9.
65. Koetter P, Pelton M, Gonzalo J, Du P, Exten C, Bogale K, et al. Implementation and Process of a COVID-19 Contact Tracing Initiative: Leveraging Health Professional Students to Extend the Workforce During a Pandemic. Am J Infect Control. 2020.
66. State of COVID-19 Contact Tracing in the U.S. 2020 [March 29, 2021]. Available from: https://unitedstatesofcare.org/covid-19/covid-19-contact-tracing/.
67. Ruebush E, Fraser MR, Poulin A, Allen M, Lane JT, Blumenstock JS. COVID-19 Case Investigation and Contact Tracing: Early Lessons Learned and Future Opportunities. J Public Health Manag Pract. 2021;27 Suppl 1, COVID-19 and Public Health: Looking Back, Moving Forward:S87-S97.
68. Flaherty EA. School Nursing and Public Health: The Case for School Nurse Investigators and Contact Tracing Monitors of COVID-19 Patients in Massachusetts. NASN Sch Nurse. 2020;35(6):327-31.
69. Niccolai L, Shelby T, Weeks B, Schenck C, Goodwin J, Hennein R, et al. Community Trace: Rapid Establishment of a Volunteer Contact Tracing Program for COVID-19. Am J Public Health. 2020:e1-e4.
70. Lewis D. Why many countries failed at COVID contact-tracing — but some got it right. Nature. 2020.
71. Huang Z, Guo H, Lee YM, Ho EC, Ang H, Chow A. Performance of Digital Contact Tracing Tools for COVID-19 Response in Singapore: Cross-Sectional Study. JMIR Mhealth Uhealth. 2020;8(10):e23148.
72. Amit M, Kimhi H, Bader T, Chen J, Glassberg E, Benov A. Mass-surveillance technologies to fight coronavirus spread: the case of Israel. Nat Med. 2020;26(8):1167-9.
73. Covid-19 National Emergency Response Center E, Case Management Team KCfDC, Prevention. Contact Transmission of COVID-19 in South Korea: Novel Investigation Techniques for Tracing Contacts. Osong Public Health Res Perspect. 2020;11(1):60-3.
74. Maccari L, Cagno V. Do we need a contact tracing app? Comput Commun. 2021;166:9-18.
75. Chan EY, Saqib NU. Privacy concerns can explain unwillingness to download and use contact tracing apps when COVID-19 concerns are high. Comput Human Behav. 2021;119:106718.
76. Toussaert S. Upping uptake of COVID contact tracing apps. Nat Hum Behav. 2021;5(2):183-4.
77. Ferretti L, Wymant C, Kendall M, Zhao L, Nurtay A, Abeler-Dorner L, et al. Quantifying SARS-CoV-2 transmission suggests epidemic control with digital contact tracing. Science. 2020;368(6491).

78. Blom AG, Wenz A, Cornesse C, Rettig T, Fikel M, Friedel S, et al. Barriers to the Large-Scale Adoption of a COVID-19 Contact Tracing App in Germany: Survey Study. J Med Internet Res. 2021;23(3):e23362.
79. Endo A, Centre for the Mathematical Modelling of Infectious Diseases C-WG, Leclerc QJ, Knight GM, Medley GF, Atkins KE, et al. Implication of backward contact tracing in the presence of overdispersed transmission in COVID-19 outbreaks. Wellcome Open Res. 2020;5:239.
80. Clark E, Chiao EY, Amirian ES. Why contact tracing efforts have failed to curb COVID-19 transmission in much of the U.S. Clin Infect Dis. 2020.
81. Yalaman A, Basbug G, Elgin C, Galvani AP. Cross-country evidence on the association between contact tracing and COVID-19 case fatality rates. Sci Rep. 2021;11(1):2145.
82. Fetzer T, Graeber T. Does Contact Tracing Work? Quasi-Experimental Evidence from an Excel Error in England. Working Paper No. 521. 2020.
83. Malheiro R, Figueiredo AL, Magalhaes JP, Teixeira P, Moita I, Moutinho MC, et al. Effectiveness of contact tracing and quarantine on reducing COVID-19 transmission: a retrospective cohort study. Public Health. 2020;189:54-9.
84. Prioritizing COVID-19 Contact Tracing Mathematical Modeling Methods and Findings 2020 [March 29, 2021]. Available from: https://www.cdc.gov/coronavirus/2019-ncov/php/contact-tracing/contact-tracing-plan/prioritization/mathematicalmodeling.html.
85. Lash RR, Donovan CV, Fleischauer AT, Moore ZS, Harris G, Hayes S, et al. COVID-19 Contact Tracing in Two Counties - North Carolina, June-July 2020. MMWR Morb Mortal Wkly Rep. 2020;69(38):1360-3.
86. Miller JS, Bonacci RA, Lash RR, Moonan PK, Houck P, Van Meter JJ, et al. COVID-19 Case Investigation and Contact Tracing in Central Washington State, June-July 2020. J Community Health. 2021.
87. Sachdev DD, Brosnan HK, Reid MJA, Kirian M, Cohen SE, Nguyen TQ, et al. Outcomes of Contact Tracing in San Francisco, California—Test and Trace During Shelter-in-Place. JAMA Internal Medicine. 2021;181(3):381-3.
88. Steens A, Freiesleben de Blasio B, Veneti L, Gimma A, Edmunds WJ, Van Zandvoort K, et al. Poor self-reported adherence to COVID-19-related quarantine/isolation requests, Norway, April to July 2020. Euro Surveill. 2020;25(37).
89. Smith LE, Potts HWW, Amlot R, Fear NT, Michie S, Rubin GJ. Adherence to the test, trace, and isolate system in the UK: results from 37 nationally representative surveys. BMJ. 2021;372:n608.
90. Smith LE, Amlot R, Lambert H, Oliver I, Robin C, Yardley L, et al. Factors associated with adherence to self-isolation and lockdown measures in the UK: a cross-sectional survey. Public Health. 2020;187:41-52.
91. Jenniskens K, Bootsma MCJ, Damen J, Oerbekke MS, Vernooij RWM, Spijker R, et al. Effectiveness of contact tracing apps for SARS-CoV-2: a rapid systematic review. BMJ Open. 2021;11(7):e050519.
92. Braithwaite I, Callender T, Bullock M, Aldridge RW. Automated and partly automated contact tracing: a systematic review to inform the control of COVID-19. Lancet Digit Health. 2020;2(11):e607-e21.

93. Glasgow RE, Harden SM, Gaglio B, Rabin B, Smith ML, Porter GC, et al. RE-AIM Planning and Evaluation Framework: Adapting to New Science and Practice With a 20-Year Review. Front Public Health. 2019;7:64.
94. Clarke V, Braun V. Thematic Analysis. In: Teo T, editor. Encyclopedia of Critical Psychology. New York, NY: Springer New York; 2014. p. 1947-52.
95. Michie S, van Stralen MM, West R. The behaviour change wheel: a new method for characterising and designing behaviour change interventions. Implement Sci. 2011;6:42.

Chapter Two. Lessons learned from COVID-19 contact tracing during a public health emergency: a prospective implementation study

Tyler Shelby[1,2,†], Christopher Schenck[2,†], Brian Weeks[3,†], Justin Goodwin[1,2], Rachel Hennein[1,2], Xin Zhou[4,5], Donna Spiegelman[4,5], Lauretta E. Grau[1], Linda Niccolai[1], Maritza Bond[3,†], J. Lucian Davis[1,5,6,†]

† These authors contributed equally[*]
1. Department of Epidemiology of Microbial Diseases, Yale School of Public Health, New Haven, CT, USA
2. Yale School of Medicine, New Haven, CT, USA
3. New Haven Health Department, New Haven, CT, USA
4. Department Biostatistics, Yale School of Public Health, New Haven, CT, USA
5. Center for Methods in Implementation and Prevention Science, Yale School of Public Health, New Haven, CT, USA
6. Pulmonary, Critical Care, and Sleep Medicine Section, Yale School of Medicine, New Haven, CT, USA

This manuscript has been previously published as:

Shelby T, Schenck C, Weeks B, Goodwin J, Hennein R, Zhou X, et al. Lessons Learned From COVID-19 Contact Tracing During a Public Health Emergency: A Prospective Implementation Study. Frontiers in Public Health. 2021; 9(1196).

[*]*TS's contributions included study conceptualization, data collection and curation, formal analysis, initial drafting and revision of manuscript, tables, and figures.*

2.1 Abstract

Background: Contact tracing is a core element of the public health response to emerging infectious diseases including COVID-19. Better understanding the implementation context of contact tracing for pandemics, including individual- and systems-level predictors of success, is critical to preparing for future epidemics.

Methods: We carried out a prospective implementation study of an emergency volunteer contact tracing program established in New Haven, Connecticut between April 4 and May 19, 2020. We assessed the yield and timeliness of case and contact outreach in reference to CDC benchmarks, and identified individual and programmatic predictors of successful implementation using multivariable regression models. We synthesized our findings using the RE-AIM implementation framework.

Results: Case investigators interviewed only 826 (48%) of 1,705 cases and were unable to reach 545 (32%) because of incomplete information and 334 (20%) who missed or declined repeated outreach calls. Contact notifiers reached just 687 (28%) of 2,437 reported contacts, and were unable to reach 1,597 (66%) with incomplete information and 153 (6%) who missed or declined repeated outreach calls. The median time-to-case-interview was 5 days and time-to-contact-notification 8 days. However, among notified contacts with complete time data, 457 (71%) were reached within 6 days of exposure. The least likely groups to be interviewed were elderly (adjusted relative risk, aRR 0.74, 95% CI 0.61–0.89, $p = 0.012$, vs. young adult) and Black/African-American cases (aRR 0.88, 95% CI 0.80–0.97, pairwise $p = 0.01$, vs. Hispanic/Latinx). However, ties between cases and their contacts strongly influenced contact notification success (Intraclass Correlation Coefficient (ICC) 0.60). Surging caseloads and high volunteer turnover (case investigator n = 144, median time from sign-up to retirement from program was 4 weeks) required the program to supplement the volunteer workforce with paid public health nurses.

Conclusions: An emergency volunteer-run contact tracing program fell short of CDC benchmarks for time and yield, largely due to difficulty collecting the information required for outreach to cases and contacts. To improve uptake, contact tracing programs must professionalize the workforce; better integrate testing and tracing services; capitalize on positive social influences between cases and contacts; and address racial and age-related disparities through enhanced community engagement.

2.2 Introduction

Coronavirus Disease 2019 (COVID-19) emerged in late 2019 and rapidly spread throughout the world with dramatic effects on health systems and societies (1). Contact tracing and other non-pharmaceutical interventions have assumed critical importance for limiting the spread of SARS-CoV-2 (2) and will remain important in protecting unvaccinated populations and responding to breakthrough transmission from variant strains. Contact tracing is a complex intervention that involves isolating and investigating cases while eliciting, quarantining, and monitoring their close contacts. Although, contact tracing is effective for mitigating many communicable diseases including sexually transmitted infections (3) and tuberculosis (4), it must be tailored to the clinical features and transmission dynamics of the causative pathogen, as well as the local epidemiological context and resources. In East Asia, e.g., contact tracing was rapidly and effectively adapted for COVID-19 thanks to early and massive political and financial investments, informed by prior experiences with Severe Acute Respiratory Syndrome (SARS) (5) and Middle East Respiratory Syndrome (MERS) (6) and largely receptive societies. When combined with other preventive measures including physical distancing, universal masking, and digital tracking, contact tracing for COVID-19 has been shown to reduce the effective reproductive number (R_0) (7), secondary attack rates (8) and case fatality rates (9, 10) and to contain outbreaks and generalized epidemics in diverse settings (10-12). Nevertheless, contact tracing has not proven effective everywhere (13) (14), and many have questioned its overall usefulness in the recent pandemic (15).

Given these uncertainties, a better understanding of the implementation of contact tracing is critical to learning from the COVID-19 pandemic and preparing for the future. Modeling suggests that the effectiveness of contact tracing depends on the speed and efficiency with which cases are isolated and contacts quarantined (16). Target benchmarks proposed by the U.S. Centers for Disease Control and Prevention (CDC) include successfully investigating ≥60% of cases and placing their contacts in quarantine within 6 days of exposure (17). While media outlets have covered implementation of contact tracing extensively, very few scientific reports have evaluated the implementation fidelity or context or explored individual or health system risk factors for dropping out of contact tracing (18-21). Therefore, we sought to evaluate measures and determinants of implementation for a COVID-19 contact tracing program rapidly established in New Haven, Connecticut in early 2020.

2.3 Methods

Setting and Contact Tracing Procedures

New Haven, a racially and ethnically diverse city of 130,250 residents (33% Black/African-American, 31% Hispanic/Latinx, 30% White, 5% Asian) (22) confirmed its first COVID-19 cases in mid-March 2020. Working together, the New Haven Health Department (NHHD) and the Yale School of Public Health launched an emergency contact tracing program for the City of New Haven on April 4 using the city's existing emergency management software (Veoci, New Haven, CT). Students, faculty, and staff in the graduate health sciences at Yale University were recruited into a volunteer workforce of 151 case investigators and 36 contact notifiers (both henceforth labeled “contact tracers”), as previously described (23). In early April, 40 public health nurses from the NHHD were added to the case investigation team.

Each day, the city's lead epidemiologist sent a list of newly reported COVID-19 cases to volunteer leaders, who then assigned them to case investigators. Case investigators were instructed to telephone cases within 24 h and identify close contacts, defined as those with whom the case had spent ≥15 min within a six-foot radius during the infectious period (24). If a case did not answer, investigators were instructed to leave a voicemail message and try again daily for 3 days.

Contact names, phone numbers and exposure dates (henceforth termed “outreach information”) were securely emailed to volunteer coordinators for distribution to contact notifiers. Notifiers telephoned contacts to inform them about their exposure to COVID-19, and counsel them to self-monitor for symptoms, seek testing if symptomatic, and self-quarantine for 14 days after the last exposure date. Contacts were not called if missing outreach information or if reported >14 days after exposure.

Study Design and Participants

We evaluated each of the processes involved implementing contact tracing using quantitative data recorded for the NHHD. We included all COVID-19 cases with a specimen collection date between April 4 and May 19 (when Connecticut began reopening businesses), except cases residing in congregate settings (e.g., nursing homes). We included all close contacts of eligible cases.

Measurements and Outcomes

We obtained demographic data for cases and contacts and dates of testing and tracing events from local registries. We defined six key steps of contact tracing (Supplementary Figure 2.1), beginning with collection of the diagnostic specimen from the case. These included [1] reporting cases to the NHHD, [2] telephoning cases, [3] interviewing cases, [4] reporting contacts, [5] telephoning contacts, and [6] notifying contacts. We produced indicators of yield and timeliness for each step and used the CDC target benchmarks as specified above (17). To quantify the availability of human resources, we used shift records to estimate the weekly person-hours contributed by public health nurses and volunteers.

Analysis Plan

We presented characteristics of telephoned cases and contacts using proportions for dichotomous variables and medians with quartiles for continuous variables. We calculated yield indicators as stepwise and cumulative proportions and presented them using flow diagrams and a descriptive cascade. We calculated timeliness indicators as the cumulative time from specimen collection to completion of key processes and presented them using violin plots. We excluded observations with missing or non-sensical time values (e.g., notification date preceding outreach date).

In addition, we constructed three multivariable models using generalized estimating equations (GEE) (25), employing a log link function to obtain multivariable-adjusted relative risks (aRR) for each covariate. Each model evaluated the associations between case, contact, and program characteristics and indicators of success at one of three points in the cascade: [A] completion of the case interview for all cases telephoned, [B] collection of outreach information for all contacts, and [C] completion of notification for all contacts telephoned. We included all case, contact, and program covariates in the models, as long as there were at least 10 outcomes per variable (26). We grouped categorical responses with fewer than 10 outcomes and used largest categories as reference groups. We used multiple imputation (27) to account for missing covariate data and reported the results obtained using the imputed data. We included a variable for calendar week of case registration or contact identification to assess temporal trends, as well as a variable for programmatic capacity (ratio of the total contact tracer-hours available each week to incident cases or contacts to be telephoned each week). We estimated unadjusted intraclass coefficients (ICCs) using GEE (28) to account for correlation among outcomes of cases assigned to the same investigator, and outcomes of contacts elicited by the same investigator, reported by the same case, or called by the same notifier. For additional details on these analyses, see Supplementary Text Methods.

Last, we compared the weekly person-hours available to the case investigation team (supply), and incident cases to be telephoned (demand) over time, estimating a 1-h average duration for each case investigation (29), and plotted volunteer retention over time. We estimated the effect of time-since-volunteer-sign-up on weekly hours volunteered per individual with a multivariable GEE model, adjusted for calendar week of sign-up. A lack of data on characteristics of individual volunteers prevented us from adjusting for additional characteristics.

We synthesized findings using the RE-AIM framework, a widely used approach to evaluating implementation. According to RE-AIM, the Effectiveness of an intervention depends on a series of conditional processes, including uptake by participants (Reach) and implementers (Adoption), delivery (Implementation), and sustainability (Maintenance) (30). We characterized the reach of contact tracing based on indicators of yield and predictors of completion; its implementation based on timeliness; and its adoption and maintenance based on availability, demand, and retention metrics for contact tracers. Sample size was based on convenience, and statistical significance assessed in reference to a p-value < 0.05. Analyses were carried out in STATA version 16 (College Station, TX), Microsoft Excel (Redmond, WA) and SAS 9.4 (Cary, NC).

Human Subjects

The Yale Human Subjects Committee approved the study protocol and waived the requirement for informed consent on grounds of minimal risk.

2.4 Results

Study Sample and Cascade Yields

There were 1,705 COVID-19 cases reported to the NHHD during the evaluation period (Figure 2.1). Of these, 527 (31%) had missing (357, 21%), or incorrect (170, 10%) phone numbers, while 18 (1.1%) were not successfully assigned to case investigators. Among the remaining 1,160 (68%) cases telephoned, 201 (17%) did not answer or return calls, and 133 (11%) answered but declined to participate. The remaining 826 (71%) cases were interviewed, and of these, 737 (89%) reported one or more contacts. Characteristics of the 1,160 cases telephoned are shown in Table 2.1.

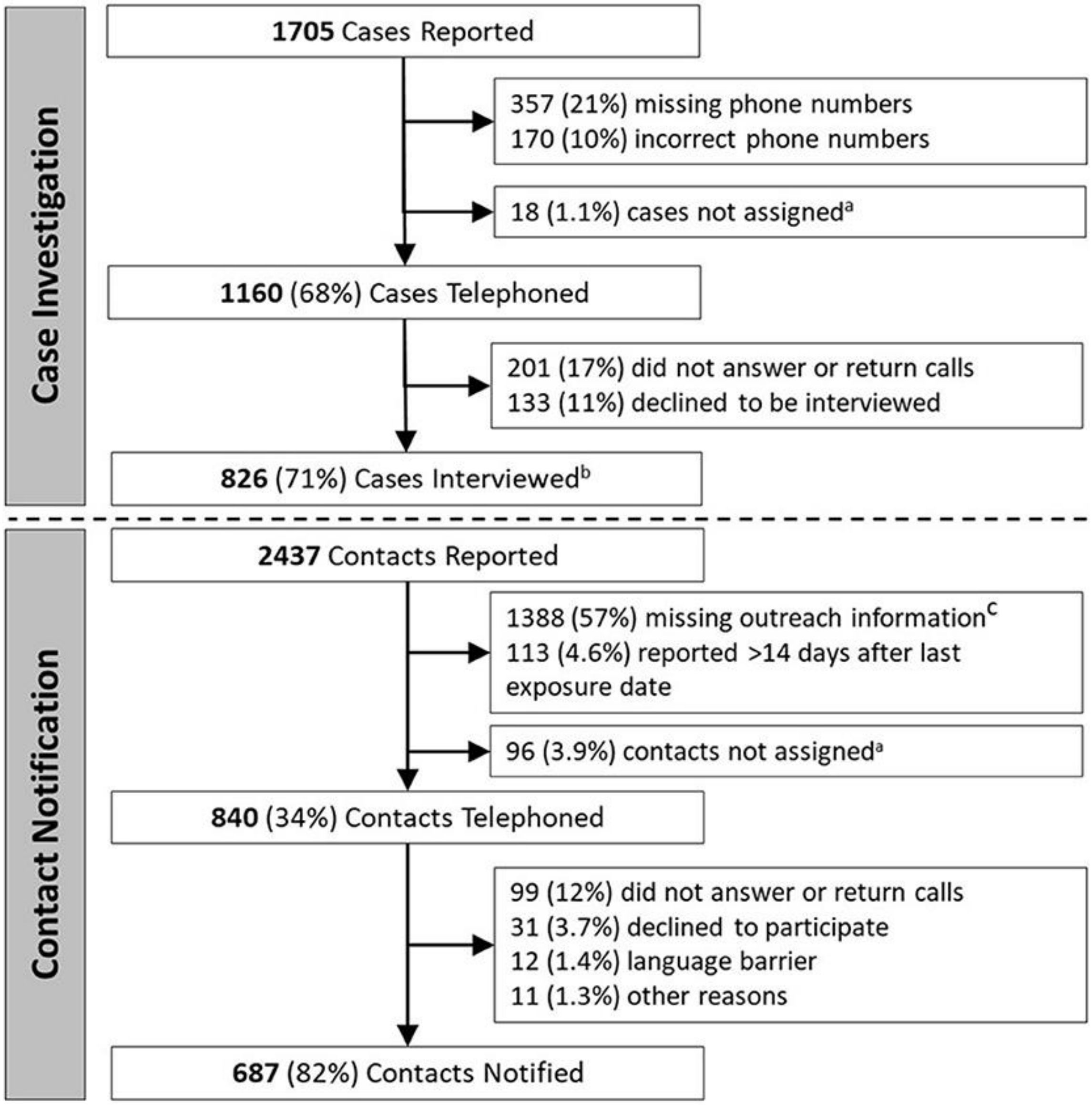


Figure 2.1. Stepwise yield of key steps of case investigation and contact notification.

Legend: [a]Cases or contacts were occasionally not successfully assigned, such as when volunteers were unable to receive assignments or when contact data was not transferred between case investigation and contact notification teams. [b]737/826 (89%) interviewed cases reported one or more contacts. [c]972/2,437 (40%) reported contacts were missing/incorrect phone number, 683/2,437 (28%) were missing last exposure date, and 341/2,437 (14%) were missing name.

Table 2.1: Baseline Characteristics of Cases Telephoned[a] and Contacts Telephoned[a]

Characteristic	n (%)[b]
Cases (n=1160)	
Age[c], median years (Q1-Q3)[d]	41 (28 - 54)
<18	64 (5.6)
18-35	384 (34)
36-50	329 (29)
51-65	244 (22)
>65	115 (10)
Female[e]	644 (57)
Race/Ethnicity[f]	
Hispanic/Latinx	537 (54)
Black/African-American	322 (32)
Caucasian/White	106 (11)
Other	30 (3.0)
Contacts (n=840)	
Age[g], median years (Q1-Q3)	32 (18 - 48)
<18	170 (24)
18-35	240 (33)
36-50	153 (21)
50-65	111 (15)
>65	44 (6.1)
Female	510 (61)
Household contact of case	695 (83)
Relationship to case	
Family member	722 (86)
Social contact	91 (11)
Work contact	27 (3.2)

Legend: [a]Baseline characteristics were not available for all cases reported or for all contacts reported. [b]Unless otherwise specified; [c]24 missing; [d]Q1 = quartile 1, Q3 = quartile 3; [e]37 missing; [f]165 missing; [g]122 missing.

Interviewed cases reported a total of 2,437 contacts (a median of 2 contacts per case) (Figure 2.1). Of these, 1,388 (57%) lacked outreach information, including 972 (40%) with missing/incorrect phone numbers, 683 (28%) with missing exposure dates, and 341 (14%) with missing names. Another 113 (4.6%) were identified >14 days after last exposure date, and 96 (3.9%) were not successfully assigned to volunteers. Of the remaining 840 (34%) who were telephoned, 687 (82%) were successfully notified, while 99 (12%) did not answer or return calls, 31 (3.7%) answered but declined to participate, 12 (1.4%) were not reached due to language barriers, and 11 (1.3%) were not reached for other reasons. The characteristics of the 840 contacts telephoned are shown in Table 2.1.

Ultimately, investigators interviewed 48% of all cases, with 32% lost before being telephoned and 20% lost before being interviewed (Supplementary Figure 2.2). Of all contacts, 28% were notified, with 66% lost before being telephoned, and 6% lost before being notified.

Timeliness

The median time from case specimen collection to case reporting to NHHD was 2 days (Quartile 1 (Q1) - Quartile 3 (Q3): 2–4); to telephoning cases, 4 days (Q1–Q3: 3–5); and to case interview, 5 days (Q1–Q3: 4–8) (Figure 2.2). The median time to contact reporting was 5 days (Q1–Q3: 4–8); to telephoning contacts, 7 days (Q1–Q3: 5–9); and to contact notification, 8 days (Q1–Q3: 6–11). Among the 648 notified contacts with valid dates recorded for most recent exposure and notification, 457 (71%) were notified within 6 days of their exposure.

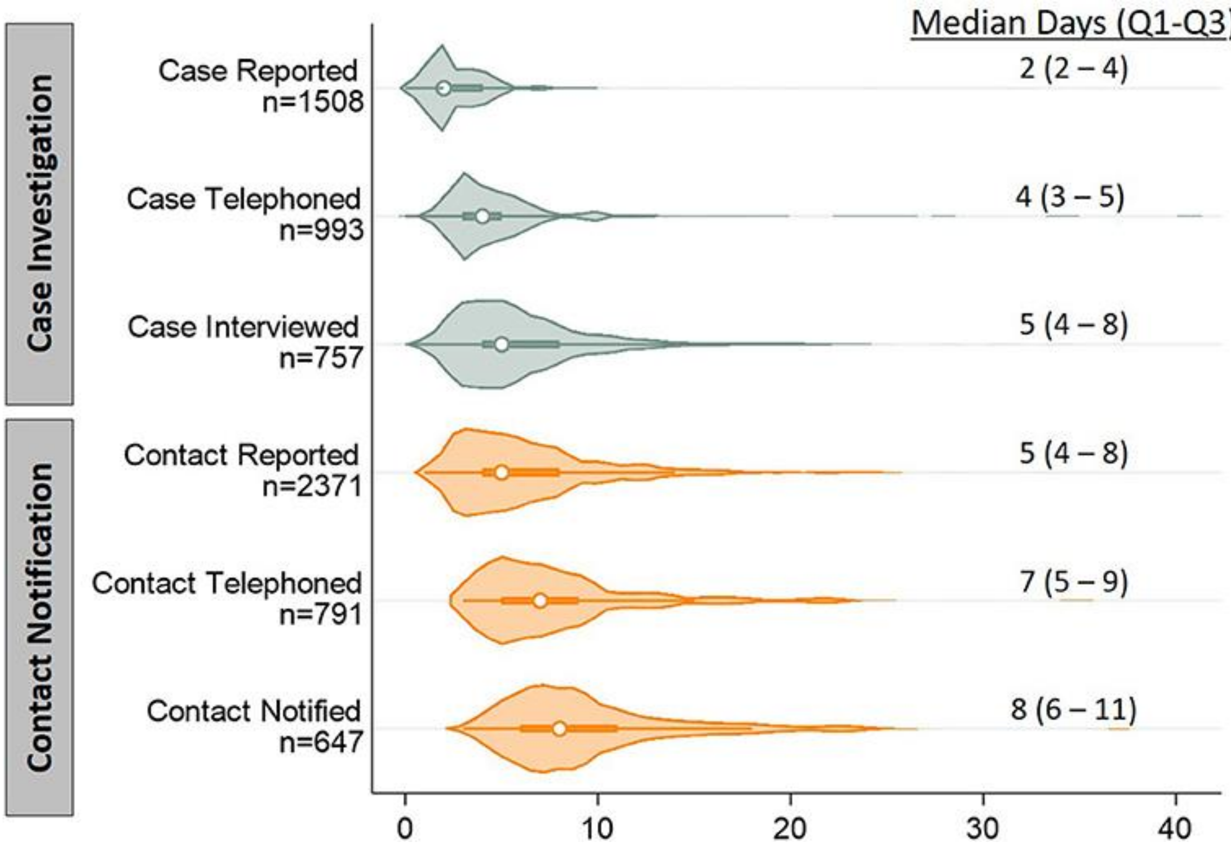


Figure 2.2. Violin plots depicting distributions of timeliness indicators for key steps of contact tracing, in days. Timeliness indicators were calculated as the cumulative time from specimen collection from a case to completion of each of the six steps of contact tracing (subdivided into case investigation and contact notification). Each indicator includes only participants who completed that step and had the initiation and completion times recorded. The displayed n's differ from those presented in Figure 1 because of missing time data (either the case's report date or any subsequent event date). We also excluded 29 contact observations with non-sensical time values (e.g., notification date preceding outreach date). Violin plots show distributions as a shaded, smoothed kernel density estimator; inside the distribution plot, medians are plotted as an open circle and the upper and lower quartile range is plotted as a bolded line.

Factors Associated with Successful Implementation

Among 1,160 cases telephoned, several factors were significantly associated with interview completion (Supplementary Table 2.1). The probability of being interviewed was lower for the elderly (aRR for >65 years old vs. young adult (18–35 years): 0.74, 95% CI 0.61–0.89, $p = 0.012$). Although race as a whole was not a significant predictor, Black/African American cases were significantly less likely than Hispanic/Latinx cases to be interviewed (aRR: 0.88, 95% CI 0.80–0.97, pairwise $p = 0.01$). Furthermore, the probability of success decreased by 3% for each calendar week following initiation of the program (aRR: 0.97, 95% CI 0.94–0.99, $p = 0.020$). Success rates did not vary substantially among interviewers (ICC = 0.002).

Among the 2,437 contacts reported, the probability of collecting all required outreach information was lower for contacts reported by cases aged 36–50 years old (aRR 0.83, 95% CI 0.73–0.93, $p = 0.008$, vs. young adult cases). Probability of collecting outreach information was also lower for contacts <18 years vs. young adult (aRR 0.63, 95% CI 0.54–0.72, $p < 0.001$), non-household vs. household contacts (aRR 0.88, 95% CI 0.77–1.00, $p = 0.0495$), social vs. family contacts (aRR 0.77, 95% CI 0.65–0.91, $p < 0.001$) and work vs. family contacts (aRR 0.57, 95% CI 0.44–0.74, $p < 0.001$) (Supplementary Table 2.2). Success rates varied by case interviewer (ICC = 0.21), suggesting that the way questions are asked may influence outcomes. Success rates also varied by case cluster (ICC = 0.45), indicating that cases who provide outreach information for any individual contact are more likely to provide it for other contacts they report.

For the 840 contacts telephoned, the probability of notification was influenced by the ratio of contact notifiers to contacts (aRR 1.43, 95% CI 1.04–1.95, $p = 0.026$) (Supplementary Table 2.3). Notification rates varied only modestly by contact notifier (ICC = 0.14) but varied more substantially by case cluster (ICC = 0.60), suggesting that ties between cases and their contacts may influence the success of contact outreach.

Volunteer Case Investigator Adoption and Maintenance

The supply of available case investigators exceeded demand for case investigation in all weeks (Figure 2.3A; contact notifiers presented in Supplementary Figure 2.3), although it was necessary to add public health nurses during the program's second week to meet demand. Case investigation volunteers offered a median of 4 h during their first week and decreased involvement by 0.68 h per calendar week in the program (95%CI −0.84 to −0.51, $p < 0.0001$; Supplementary Table 2.4), with a median time of 4 weeks (95% CI 3–5; Figure 2.3B) from signing-up for to retiring from the program.

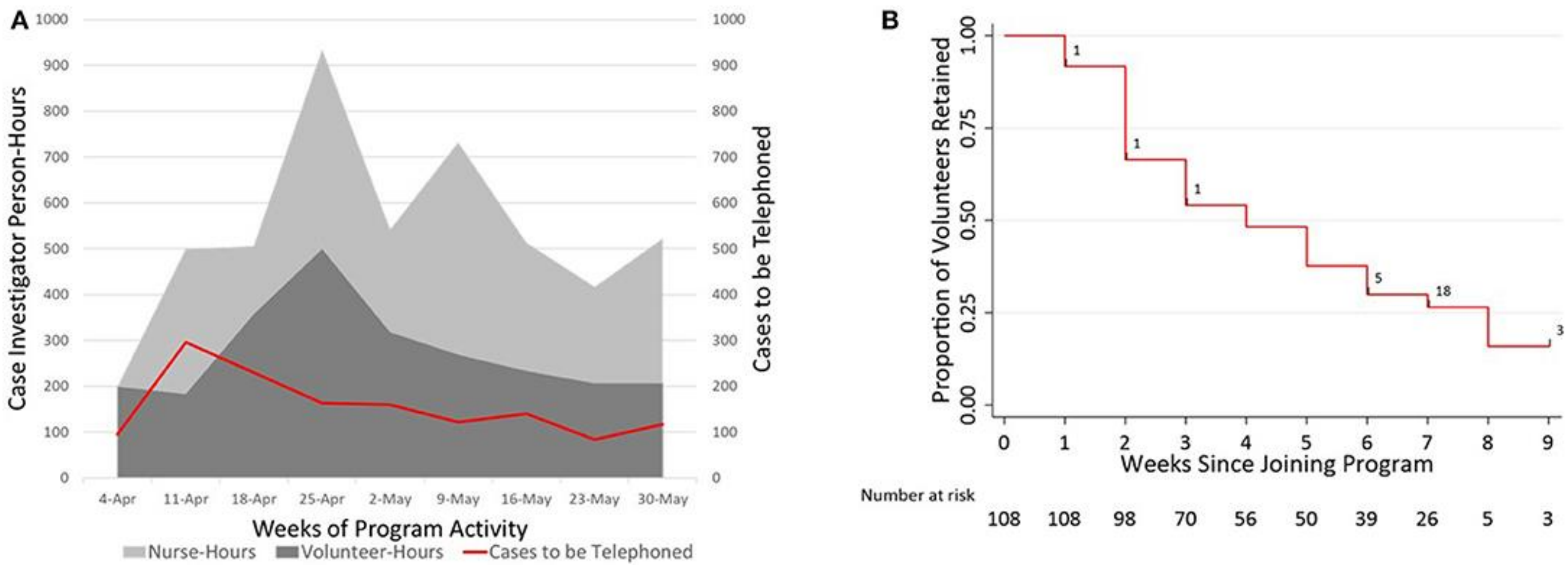


Figure 2.3. Plots showing supply and demand, and retention of the case investigation workforce over time. (A) Contour plot comparing the supply of case investigator time (in person-hours, left axis, volunteers and nurses stacked) to the demand for case investigation (in cases assigned to be telephoned per week, right axis) for each calendar week of program activity. Assuming (conservatively) that an average of 1 h is required to perform and document case investigation (29), the supply of volunteer case investigator time exceeded demand for case investigation in all weeks except the week beginning 11-Apr, when 40 public health nurses were first recruited. (B) Retention of case-investigation volunteers (n = 108) over time, shown using a survival plot against time from joining until the outcome of leaving the New Haven contact tracing program. Right censoring is noted with black hash marks overlaid on the survival curve, with the corresponding n.

2.5 Discussion

This systematic and structured evaluation of the core processes involved in COVID-19 contact tracing enabled us to quantify the uptake and efficiency of implementation and identify factors influencing its delivery. In this prospective evaluation, we found that low yield and timeliness metrics were closely linked to delays in test reporting and data transfer, incomplete or incorrect outreach information, and limited success in reaching cases and contacts by telephone. We also identified case, contact, and programmatic factors associated with success. Last, we observed high rates of adoption of contact tracing among volunteers, but also high rates of turnover. Below, we use the RE-AIM framework to contextualize our findings and propose potential solutions to improve the delivery of contact tracing for current and future pandemics (Table 2.2).

Table 2.2: Potential solutions for identified challenges, by RE-AIM dimension

RE-AIM Dimension	Challenges	Potential Solutions
Reach	Lack of required outreach data	Collect case phone numbers and initiate linkage to contact tracing at time-of-testing Identify messaging strategies (e.g., education regarding importance of contact tracing, security of data, and benefits of contact tracing to one's community, etc.) to increase completion of evaluation
	Lower outreach success among the elderly	Prioritize outreach calls to those most at risk and tailor engagement strategies to client needs and preferences
	Unmeasured characteristics of tracers and cases that influence success in contact outreach	Identify characteristics of tracers, tracer-case dyads, and case social networks that influence success in order to improve and standardize training and outreach strategies Evaluate strategies for engaging cases in linking contacts to the health department without infringing on privacy or promoting stigma (e.g., training cases to notify their contacts of exposure and inform them of incoming calls from the health department)
Implementation	Delays in test reporting and data transfer	Use same-day electronic linkage to A) share test results from the lab with contact tracing programs and B) make case and contact assignments to contact tracers
	Delays between case and contact outreach attempts	Integrate outreach to cases and their household contacts, as is done with household contact investigation for tuberculosis
Adoption and Maintenance	High turnover amongst volunteer contact tracers	Offer financial or educational incentives to increase sustainability of the contact tracing workforce

In previous reports, the yield of COVID-19 contact tracing varies widely, with interview success rates ranging 33–100% (13, 18-20, 31) and the proportions of cases reporting contacts ranging 7–100% (13, 19, 20, 31). In our study, missing or incorrect information (e.g., names, phone numbers) was the most significant barrier to *Reach*, affecting nearly one-third of cases and over half of reported contacts. This surprising barrier reflects a hesitancy or inability of many cases to provide complete outreach information for their contacts, which should be explored in future studies. It also reflects a failure of independent testing sites to collect case phone numbers at the time-of-testing. In the haste to establish sufficient numbers of testing sites, the opportunity to link this service with downstream contact tracing was overlooked by many. While some states reported similar challenges to obtaining this information (32) early in the pandemic, by the end of the first year of the pandemic some reported near complete capture of accurate phone numbers (33). These improvements reflect the impact of redesigning care processes, and additional insights into contact tracing efficiency may be found in other disease contexts (4). In contact tracing for tuberculosis, for example, outreach information is rarely missing because case investigation is introduced at diagnosis or treatment initiation and contacts are frequently evaluated in-person during household or office visits. Consequently, tracers in multiple settings routinely reach >80% of tuberculosis contacts (34, 35). While large COVID-19 caseloads and limited personal protective equipment made in-person contact tracing infeasible throughout much of pandemic, the practice of introducing contact tracing and verifying outreach preferences at diagnosis (or earlier at the time of testing) could also be adopted for COVID-19.

We additionally found that individual case characteristics strongly influenced outreach success. The lower likelihood of successful outreach to the elderly is concerning given their increased risk of severe disease (36, 37). While the association of all race/ethnicity categories with successful outreach to cases just missed the significance threshold ($p = 0.054$) after adjustment for time and other potentially confounding factors, the statistical power of the analysis may have been limited by the sample size. Nevertheless, our precision estimates comparing Black and Hispanic/Latinx cases consistently excluded the null hypothesis, suggesting that Black cases were significantly less likely to be interviewed. Both older age and non-white race/ethnicity have been associated with more severe disease and higher mortality (36-38) and improving the reach and timeliness of contact tracing may offer opportunities to intervene earlier to improve individual outcomes. Future studies should continue to explore differences in outcomes across population groups, given that pre-existing health inequities have been amplified by the pandemic (38, 39). In particular, while we were only able to evaluate differences in interview and notification outcomes, future studies should also evaluate predictors of successful isolation and quarantine. Future contact tracing programs should also strive to collect comprehensive race/ethnicity data to help identify and address disparities in access to COVID care (38).

Case and tracer characteristics also appeared to influence contact outcomes, with strong correlations between outcomes of contacts reported by the same cases, elicited by the same investigators, or called by the same notifiers. To standardize training of contact tracers and inform best practices, future studies should explore which characteristics and behaviors of these individuals, dyads, or networks influence success. In the area of HIV partner notification (40), for comparison, index cases often prefer to notify and refer their own contacts for evaluation, an approach that could also be considered for COVID-19.

In terms of *Implementation*, slow test reporting and data transfer led to the most significant delays, as reported elsewhere (18-20). Considering the transmissibility of SARS-CoV-2 and the risks of each day of delay, same-day test results, electronic reporting to public health databases, and early outreach could be better prioritized and even incentivized. In addition, case and contact outreach could be integrated so that all household members are notified concurrently rather than sequentially to improve timeliness and uptake among contacts.

Elsewhere, the ratio of contact tracers to cases and contacts was found to be associated with timeliness and number of contacts identified (21). In evaluating *Adoption*, we found volunteers to be a feasible, although not sustainable, solution to human resource shortages, given the high turnover among volunteers. We separately conducted focus groups with volunteers, described in detail elsewhere (41), who reported that burnout and transitions in academic roles and schedules likely contributed to decreased volunteer availability. Fortunately, the support of public health nurses bolstered capacity during surges and sustained the program. Further research is needed to identify strategies to improve the *Maintenance* of volunteer-driven programs, such as requesting fixed weekly time commitments and offering academic credit or small stipends to incentivize retention.

Many COVID-19 contact tracing programs, including the one evaluated here, struggled to meet CDC's yield and timeliness benchmarks for effective case and contact outreach (16, 17). While the yield of this program was significantly limited by barriers beyond the control of the NHHD (e.g., missing phone number data from independent testing sites, hesitancy or inability of cases to fully report contacts, etc.,), this program still managed to reach nearly 70% of all actionable cases (those with phone numbers) with a median time of 5 days from reporting. They also managed to reach 82% of all actionable contacts (those with requisite outreach information), of whom nearly 70% were reached within 6 days of their exposure. Given the immense constraints on resources and time to establish the emergency response, these outcomes are commendable, even if falling short of target benchmarks.

It is also important to note that there is value to tracing even when it falls short of such benchmarks. While the modeling studies used to derive target benchmarks consider contact tracing as a stand-alone intervention (16), in practice, it is bundled with other interventions, so that contact tracing serves additional pandemic objectives, including health education and linkage to social support (nutritional, financial, etc.), testing, medical care, and vaccination. Bundling interventions to enhance impact is critical to solve what might be described as the pandemic's “Swiss cheese” problem, in which holes in the clinical and public health response arise at multiple levels, times, and locations to sustain the pandemic (42). Qualitative data collected in parallel with this project and published separately (41) supports this idea that even if contact tracing itself has gaps, it may still contribute to the overall public health response. Limited retrospective data from other settings also suggests that contact tracing may also contribute to improved cumulative outcomes (7), and this important question should be evaluated further in future prospective studies.

This study had several important strengths, including its prospective design and use of detailed participant data to identify challenges to and predictors of each step of the process. It is among the first reports on implementation outcomes of contact tracing for COVID-19 in North America and provides insights into resource allocation and volunteer deployment during the early, crisis stage of the COVID-19 pandemic. Insights from this phase of the pandemic will not only help guide intervention adaptations throughout the subsequent phases of the COVID-19 pandemic but will also help inform responses to future epidemics and pandemics. Last, New Haven has a high level of racial and ethnic diversity, providing an appropriate setting for understanding inequities in implementation processes and outcomes.

There were also some limitations. First, missing demographic data may have biased our analyses in uncertain ways, but we used multiple imputation to help reduce such biases in our models. Second, we did not capture the reasons for unanswered calls, or for refusals to participate, although the viewpoints and experiences of volunteer contacts are presented in detail elsewhere (41), and separate studies will report the viewpoints of cases and contacts regarding these and other barriers to uptake. Third, we could not evaluate under-reporting of contacts and therefore may have overestimated the proportion of contacts reached. Fourth, we were unable to report on effectiveness outcomes such as the proportion of contacts infected because test availability was extremely limited early in the pandemic. Last, these data were collected during the initial months of the COVID-19 pandemic but contact tracing strategies and barriers have evolved substantially since that time. Nevertheless, there is still much that can be learned from these findings from the initial phase of the pandemic to improve ongoing and future pandemic response efforts, as many related challenges persist.

In conclusion, in this large public health evaluation of an early, volunteer-driven contact tracing program, we found that yield was significantly reduced by missing case and contact information and that timeliness was limited by slow test reporting and data transfer. Volunteers were a feasible but short-term source of contact tracers, and many case, contact, and program characteristics appeared to influence success. Together, these findings point to opportunities for process redesign to increase the impact of contact tracing, with a focus on integrated data management, engagement of all communities, and better understanding of the positive social influences between cases and contacts.

2.6 References

1. Blumenthal D, Fowler EJ, Abrams M, Collins SR. Covid-19 - Implications for the Health Care System. N Engl J Med. 2020;383(15):1483-8.
2. Watson C, Cicero A, Blumenstock J, Fraser M. A National Plan to Enable Comprehensive COVID-19 Case Finding and Contact Tracing in the US. The Johns Hopkins Center for Health Security. 2020.
3. Mahachi N, Muchedzi A, Tafuma TA, Mawora P, Kariuki L, Semo BW, et al. Sustained high HIV case-finding through index testing and partner notification services: experiences from three provinces in Zimbabwe. J Int AIDS Soc. 2019;22 Suppl 3:e25321.
4. Hopewell PC, Reichman LB, Castro KG. Parallels and Mutual Lessons in Tuberculosis and COVID-19 Transmission, Prevention, and Control. Emerg Infect Dis. 2021;27(3):681-6.
5. Ooi PL, Lim S, Chew SK. Use of quarantine in the control of SARS in Singapore. Am J Infect Control. 2005;33(5):252-7.
6. Lim PL. Middle East respiratory syndrome (MERS) in Asia: lessons gleaned from the South Korean outbreak. Trans R Soc Trop Med Hyg. 2015;109(9):541-2.
7. Pan A, Liu L, Wang C, Guo H, Hao X, Wang Q, et al. Association of Public Health Interventions With the Epidemiology of the COVID-19 Outbreak in Wuhan, China. JAMA. 2020;323(19):1915-23.
8. Cheng HY, Jian SW, Liu DP, Ng TC, Huang WT, Lin HH, et al. Contact Tracing Assessment of COVID-19 Transmission Dynamics in Taiwan and Risk at Different Exposure Periods Before and After Symptom Onset. JAMA Intern Med. 2020;180(9):1156-63.
9. Fetzer T, Graeber T. Does Contact Tracing Work? Quasi-Experimental Evidence from an Excel Error in England. Working Paper No. 521. 2020.
10. Yalaman A, Basbug G, Elgin C, Galvani AP. Cross-country evidence on the association between contact tracing and COVID-19 case fatality rates. Sci Rep. 2021;11(1):2145.
11. Valent F, Gallo T, Mazzolini E, Pipan C, Sartor A, Merelli M, et al. A cluster of COVID-19 cases in a small Italian town: a successful example of contact tracing and swab collection. Clin Microbiol Infect. 2020;26(8):1112-4.
12. Jian SW, Cheng HY, Huang XT, Liu DP. Contact tracing with digital assistance in Taiwan's COVID-19 outbreak response. Int J Infect Dis. 2020;101:348-52.
13. Lash RR, Moonan PK, Byers BL, Bonacci RA, Bonner KE, Donahue M, et al. COVID-19 Case Investigation and Contact Tracing in the US, 2020. JAMA Network Open. 2021;4(6):e2115850-e.
14. Malheiro R, Figueiredo AL, Magalhaes JP, Teixeira P, Moita I, Moutinho MC, et al. Effectiveness of contact tracing and quarantine on reducing COVID-19 transmission: a retrospective cohort study. Public Health. 2020;189:54-9.
15. Clark E, Chiao EY, Amirian ES. Why contact tracing efforts have failed to curb COVID-19 transmission in much of the U.S. Clin Infect Dis. 2020.
16. Ferretti L, Wymant C, Kendall M, Zhao L, Nurtay A, Abeler-Dorner L, et al. Quantifying SARS-CoV-2 transmission suggests epidemic control with digital contact tracing. Science. 2020;368(6491).

17. Prioritizing COVID-19 Contact Tracing Mathematical Modeling Methods and Findings 2020 [March 29, 2021]. Available from: https://www.cdc.gov/coronavirus/2019-ncov/php/contact-tracing/contact-tracing-plan/prioritization/mathematicalmodeling.html.
18. Koetter P, Pelton M, Gonzalo J, Du P, Exten C, Bogale K, et al. Implementation and Process of a COVID-19 Contact Tracing Initiative: Leveraging Health Professional Students to Extend the Workforce During a Pandemic. Am J Infect Control. 2020.
19. Lash RR, Donovan CV, Fleischauer AT, Moore ZS, Harris G, Hayes S, et al. COVID-19 Contact Tracing in Two Counties - North Carolina, June-July 2020. MMWR Morb Mortal Wkly Rep. 2020;69(38):1360-3.
20. Sachdev DD, Brosnan HK, Reid MJA, Kirian M, Cohen SE, Nguyen TQ, et al. Outcomes of Contact Tracing in San Francisco, California—Test and Trace During Shelter-in-Place. JAMA Internal Medicine. 2021;181(3):381-3.
21. Spencer KD, Chung CL, Stargel A, Shultz A, Thorpe PG, Carter MW, et al. COVID-19 Case Investigation and Contact Tracing Efforts from Health Departments - United States, June 25-July 24, 2020. MMWR Morb Mortal Wkly Rep. 2021;70(3):83-7.
22. QuickFacts: New Haven City, Connecticut. Unites States Census Bureau.
23. Niccolai L, Shelby T, Weeks B, Schenck C, Goodwin J, Hennein R, et al. Community Trace: Rapid Establishment of a Volunteer Contact Tracing Program for COVID-19. Am J Public Health. 2020:e1-e4.
24. Centers for Disease Control and Prevention. Health Departments: Interim Guidance on Developing a COVID-19 Case Investigation & Contact Tracing Plan. US Department of Health and Human Services. 2020.
25. Hubbard AE, Ahern J, Fleischer NL, Van der Laan M, Lippman SA, Jewell N, et al. To GEE or not to GEE: comparing population average and mixed models for estimating the associations between neighborhood risk factors and health. Epidemiology. 2010;21(4):467-74.
26. Peduzzi P, Concato J, Kemper E, Holford TR, Feinstein AR. A simulation study of the number of events per variable in logistic regression analysis. J Clin Epidemiol. 1996;49(12):1373-9.
27. Jakobsen JC, Gluud C, Wetterslev J, Winkel P. When and how should multiple imputation be used for handling missing data in randomised clinical trials – a practical guide with flowcharts. BMC Medical Research Methodology. 2017;17(1):162.
28. Wu S, Crespi CM, Wong WK. Comparison of methods for estimating the intraclass correlation coefficient for binary responses in cancer prevention cluster randomized trials. Contemp Clin Trials. 2012;33(5):869-80.
29. Case Investigations and Contact Tracing - Frequently Asked Questions 2020 [March 29, 2021]. Available from: https://www.doh.wa.gov/Emergencies/COVID19/CaseInvestigationsandContactTracing/CaseInvestigationsandContactTracingFAQ.
30. Glasgow RE, Harden SM, Gaglio B, Rabin B, Smith ML, Porter GC, et al. RE-AIM Planning and Evaluation Framework: Adapting to New Science and Practice With a 20-Year Review. Front Public Health. 2019;7:64.
31. Miller JS, Bonacci RA, Lash RR, Moonan PK, Houck P, Van Meter JJ, et al. COVID-19 Case Investigation and Contact Tracing in Central Washington State, June-July 2020. J Community Health. 2021.

32. State of Delaware: Coronavirus (COVID-19) Data Dashboard 2021 [March 29, 2021]. Available from: https://myhealthycommunity.dhss.delaware.gov/locations/state/coronavirus-mitigation#contact_tracing.
33. New Jersey COVID-19 Dashboard 2021 [March 29, 2021]. Available from: https://www.nj.gov/health/cd/topics/covid2019_dashboard.shtml.
34. Jereb J, Etkind SC, Joglar OT, Moore M, Taylor Z. Tuberculosis contact investigations: outcomes in selected areas of the United States, 1999. Int J Tuberc Lung Dis. 2003;7(12 Suppl 3):S384-90.
35. Cavany SM, Sumner T, Vynnycky E, Flach C, White RG, Thomas HL, et al. An evaluation of tuberculosis contact investigations against national standards. Thorax. 2017;72(8):736-45.
36. Cummings MJ, Baldwin MR, Abrams D, Jacobson SD, Meyer BJ, Balough EM, et al. Epidemiology, clinical course, and outcomes of critically ill adults with COVID-19 in New York City: a prospective cohort study. medRxiv. 2020.
37. Ioannou GN, Locke E, Green P, Berry K, O'Hare AM, Shah JA, et al. Risk Factors for Hospitalization, Mechanical Ventilation, or Death Among 10131 US Veterans With SARS-CoV-2 Infection. JAMA Netw Open. 2020;3(9):e2022310.
38. Munoz-Price LS, Nattinger AB, Rivera F, Hanson R, Gmehlin CG, Perez A, et al. Racial Disparities in Incidence and Outcomes Among Patients With COVID-19. JAMA Netw Open. 2020;3(9):e2021892.
39. Berkowitz SA, Cene CW, Chatterjee A. Covid-19 and Health Equity - Time to Think Big. N Engl J Med. 2020;383(12):e76.
40. Kahabuka C, Plotkin M, Christensen A, Brown C, Njozi M, Kisendi R, et al. Addressing the First 90: A Highly Effective Partner Notification Approach Reaches Previously Undiagnosed Sexual Partners in Tanzania. AIDS Behav. 2017;21(8):2551-60.
41. Shelby T, Hennein R, Schenck C, Clark K, Meyer AJ, Goodwin J, et al. Implementation of a volunteer contact tracing program for COVID-19 in the United States: A qualitative focus group study. PLOS ONE. 2021;16(5):e0251033.
42. Reason J. Human error: models and management. West J Med. 2000;172(6):393-6.

2.7 Supplemental Information

Supplementary Table 2.1: Predictors[a] of case interview completion including all cases telephoned (n=1160)

Characteristic	Unadjusted			Adjusted		
	RR	95% CI	P-value	aRR[b]	95% CI	P-value
Age, years			0.002[c]			**0.012**[c]
<18	1.02	0.88 – 1.19		1.00	0.86 – 1.16	
18-35 (ref)	1	-		1	-	
36-50	1.00	0.91 – 1.09		1.00	0.91 – 1.08	
51-65	0.91	0.82 – 1.01		0.92	0.83 – 1.02	
>65	0.71	0.59 – 0.85		0.74	0.61 – 0.89	
Male Sex	0.97	0.90 – 1.04	0.378	0.96	0.89 – 1.04	0.302
Race/Ethnicity			0.006[c]			0.054[c]
Hispanic/Latinx (ref)	1	-		1	-	
Black/African American	0.86	0.78 – 094		0.88	0.80 – 0.97	
White	0.85	0.73 – 0.99		0.89	0.77 – 1.03	
Other	0.92	0.71 – 1.19		0.93	0.72 – 1.20	
Week since program start (1-9)	0.99	0.97 – 1.01	0.403	0.97	0.94 – 0.99	**0.020**
Capacity[d]	1.01	0.99 – 1.03	0.385	1.03	1.00 – 1.06	0.063

Abbreviations: RR, relative risk; 95% CI, 95% Confidence Interval; ref, Reference Category

Legend: [a]Estimates derived from a multivariable log-binomial GEE model; Intraclass correlation coefficient (ICC) for outreach workers=0.002. [b]Results are reported after adjusting for all other variables in the table. [c]P-value for overall significance of categorical variable. [d]Capacity measured via ratio of weekly available case investigator person-hours to weekly incident cases to be telephoned. Bolded covariates indicate covariates that were statistically significant in reference to $p<0.05$ following multivariable adjustment.

Supplementary Table 2.2: Predictors[a] of contact reporting[b] including all contacts reported (n=2437)

Characteristic	Unadjusted			Adjusted		
	RR	95% CI	p-value	aRR[c]	95% CI	p-value
Case Age, years			<0.001[d]			**0.008**[d]
<18	1.17	0.97 – 1.40		1.00	0.83 – 1.21	
18-35 (ref)	1	-		1	-	
36-50	0.83	0.73 – 0.93		0.83	0.73 – 0.93	
51-65	1.09	0.96 – 1.23		1.01	0.89 – 1.14	
>65	1.04	0.87 – 1.24		0.86	0.71 – 1.04	
Case Male Sex	0.98	0.90 – 1.08	0.721	0.95	0.86 – 1.04	0.272
Case Race/Ethnicity			0.725[d]			0.224[d]
Hispanic/Latinx (ref)	1	-		1	-	
Black/African American	0.94	0.84 – 1.06		0.89	0.79 – 1.01	
White	1.04	0.86 – 1.25		0.99	0.82 – 1.19	
Other	0.97	0.73 – 1.28		0.85	0.64 – 1.13	
Contact Age, years			<0.001[d]			**<0.001**[d]
<18	0.68	0.58 – 0.78		0.63	0.54 – 0.72	
18-35 (ref)	1	-		1	-	-
36-50	1.04	0.91 – 1.19		1.07	0.93 – 1.22	
51-65	1.08	0.93 – 1.26		1.11	0.96 – 1.29	
>65	0.99	0.80 – 1.21		1.10	0.89 – 1.34	
Contact Male Sex	0.91	0.82 – 1.00	0.054	0.94	0.85 – 1.04	0.201
Non-Household Contact	0.77	0.66 – 0.89	<0.001	0.88	0.77 – 1.00	**0.0495**
Contact Relationship to Case			<0.001[d]			**<0.001**[d]
Family member (ref)	1	-		1	-	-
Social contact	0.82	0.70 – 0.96		0.77	0.65 – 0.91	
Work contact	0.56	0.45 – 0.70		0.57	0.44 – 0.74	
Week (1 – 9)	0.98	0.95 – 1.02	0.441	0.97	0.93 – 1.01	0.109
Capacity[e]	1.00	0.96 – 1.04	0.994	1.01	0.98 – 1.05	0.492

Abbreviations: RR, relative risk; 95% CI, 95% Confidence Interval; ref, Reference Category

Legend: [a]Estimates derived from a multivariable log-binomial GEE model; Intraclass correlation coefficient (ICC) for cases = 0.45; ICC for outreach workers = 0.21. [b]Contact reporting defined as successful collection of all required outreach information (name, phone number/email, and date of exposure. [c]Results are reported after adjusting for all other variables in the table. [d]P-value for overall significance of categorical variable. [e]Capacity measured via ratio of weekly available case investigator person-hours to weekly incident cases to be telephoned. Bolded covariates indicate covariates that were statistically significant in reference to p<0.05 following multivariable adjustment.

Supplementary Table 2.3: Predictors[a] of contact notification including all contacts telephoned (n=840)

Characteristic	Unadjusted			Adjusted		
	RR	**95% CI**	**P-value**	**aRR[b]**	**95% CI**	**P-value**
Case Age, years			0.320[c]			0.144[c]
<18	1.20	0.48 – 3.01		1.01	0.47 – 2.14	
18-35 (ref)	1	-		1	-	
36-50	0.79	0.48 – 1.27		0.77	0.52 – 1.14	
51-65	0.62	0.39 – 1.01		0.61	0.42 – 0.90	
>65	0.72	0.35 – 1.46		0.72	0.42 – 1.23	
Case Male Sex	1.03	0.77 – 1.38	0.821	1.12	0.83 – 1.53	0.451
Case Race/Ethnicity			0.929[c]			0.416[c]
Hispanic/Latinx (ref)	1	-		1	-	
Black/African American	1.07	0.76 – 1.51		1.29	0.90 – 1.85	
White	1.08	0.65 – 1.78		1.14	0.69 – 1.87	
Other	1.43	0.39 – 5.24		1.98	0.54 – 7.26	
Contact Age, years			0.744[c]			0.711[c]
<18	0.92	0.62 – 1.37		0.89	0.60 – 1.34	
18-35 (ref)	1	-		1	-	
36-50	1.21	0.78 – 1.89		1.22	0.79 – 1.90	
51-65	1.12	0.68 – 1.82		1.14	0.70 – 1.85	
>65	0.87	0.48 – 1.58		0.95	0.52 – 1.74	
Contact Male Sex	1.12	0.83 – 1.51	0.451	1.11	0.82 – 1.51	0.499
Non-Household Contact	1.06	0.69 – 1.63	0.795	1.29	0.79 – 2.11	0.311
Contact Relationship to Case			0.358[c]			0.118[c]
Family member (ref)	1	-		1	-	-
Social contact	0.69	0.43 – 1.11		0.63	0.40 – 1.00	
Work contact	0.89	0.33 – 2.42		0.61	0.28 – 1.30	
Week (1 – 9)	1.13	1.03 – 1.25	0.011	1.07	0.97 – 1.18	0.155
Capacity[d]	1.61	1.10 – 2.36	0.015	1.43	1.04 – 1.95	**0.026**

Abbreviations: RR, relative risk; 95% CI, 95% Confidence Interval; ref, Reference Category

Legend: [a]Estimates derived from a multivariable log-binomial GEE model; Intraclass correlation coefficient (ICC) for cases = 0.60; ICC for outreach worker = 0.14. [b]Results are reported after adjusting for all other variables in the table. [c]P-value for overall significance of categorical variable. [d]Capacity measured via ratio of weekly available contact notifier person-hours to weekly incident contacts to be telephoned. Bolded covariates indicate covariates that were statistically significant in reference to $p<0.05$ following multivariable adjustment.

Supplementary Table 2.4: The effect of time since initial volunteer sign-up on hours volunteered per week[a]

Characteristic	Unadjusted			Adjusted		
	Hours Volunteered[b] (per week)	95% CI	P-value	Hours Volunteered[b] (per week)	95% CI	P-value
Time since initial sign-up (weeks)	**-0.67**	**-0.83 – -0.51**	**<0.001**	**-0.68**	**-0.84 – -0.51**	**<0.001**
Calendar time of sign-up			0.166[c]			0.060[c]
Week 1 (ref)	1	-		1	-	
Week 2	-1.95	-3.58 – -0.31		-2.29	-3.95 – -0.63	
Week 3	0.03	-1.49 – 1.54		-0.65	-2.25 – 0.94	
Week 4	-1.38	-2.94 – 0.18		-2.40	-4.12 – -0.68	
During or After Week 5	0.90	-2.81 – 4.61		-0.91	-4.68 – 2.85	

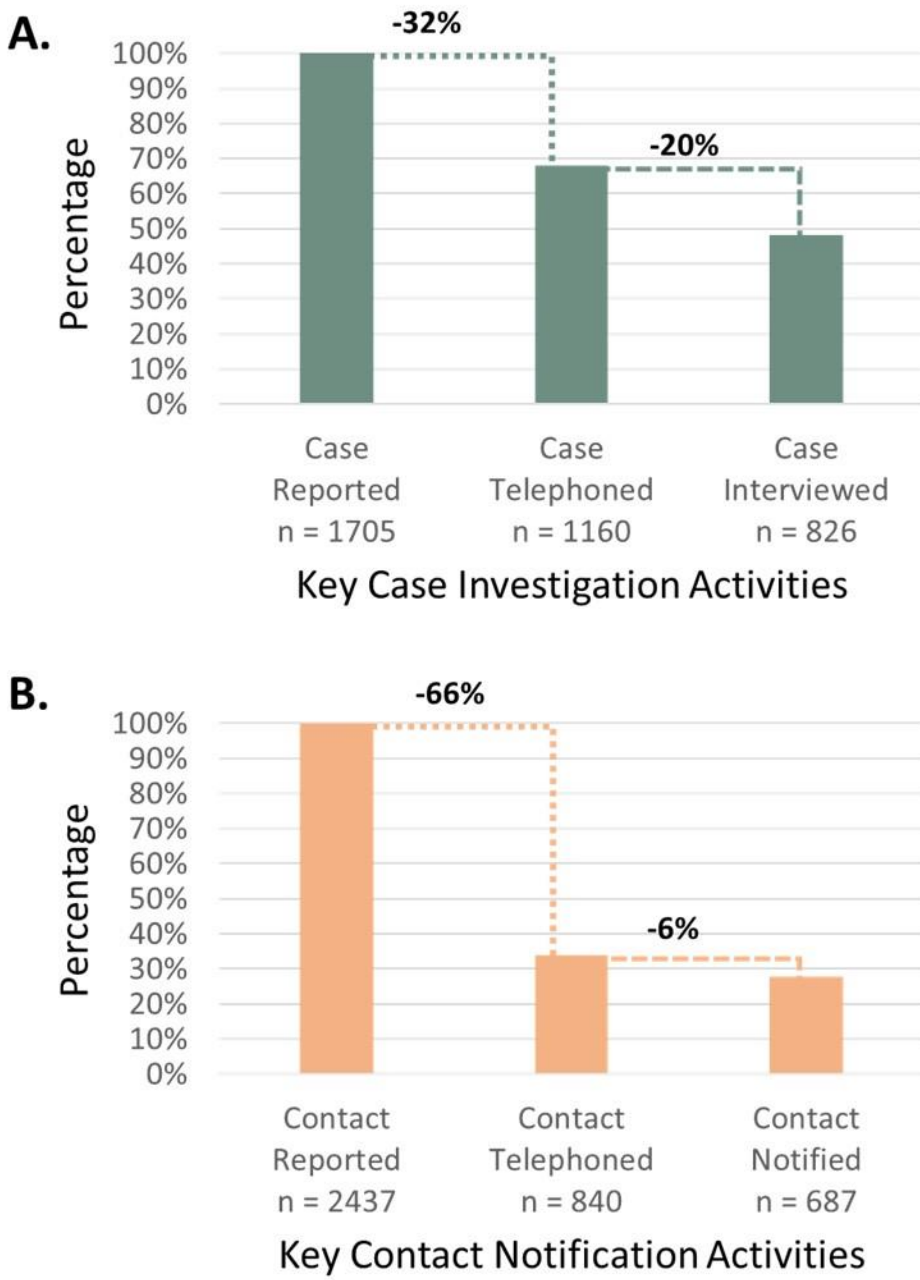
Abbreviations: 95% CI, 95% Confidence Interval; ref, Reference Category

Legend: [a]Estimates derived from a multivariable, longitudinal log-binomial GEE model. [b]Results are reported after adjusting for all other variables in the table. [c]P-value for overall significance of categorical variable. Bolded covariates indicate covariates that were statistically significant in reference to $p<0.05$ following multivariable adjustment.

Supplementary Figure 2.1: Contact Tracing Flow Diagram and Indicator Framework

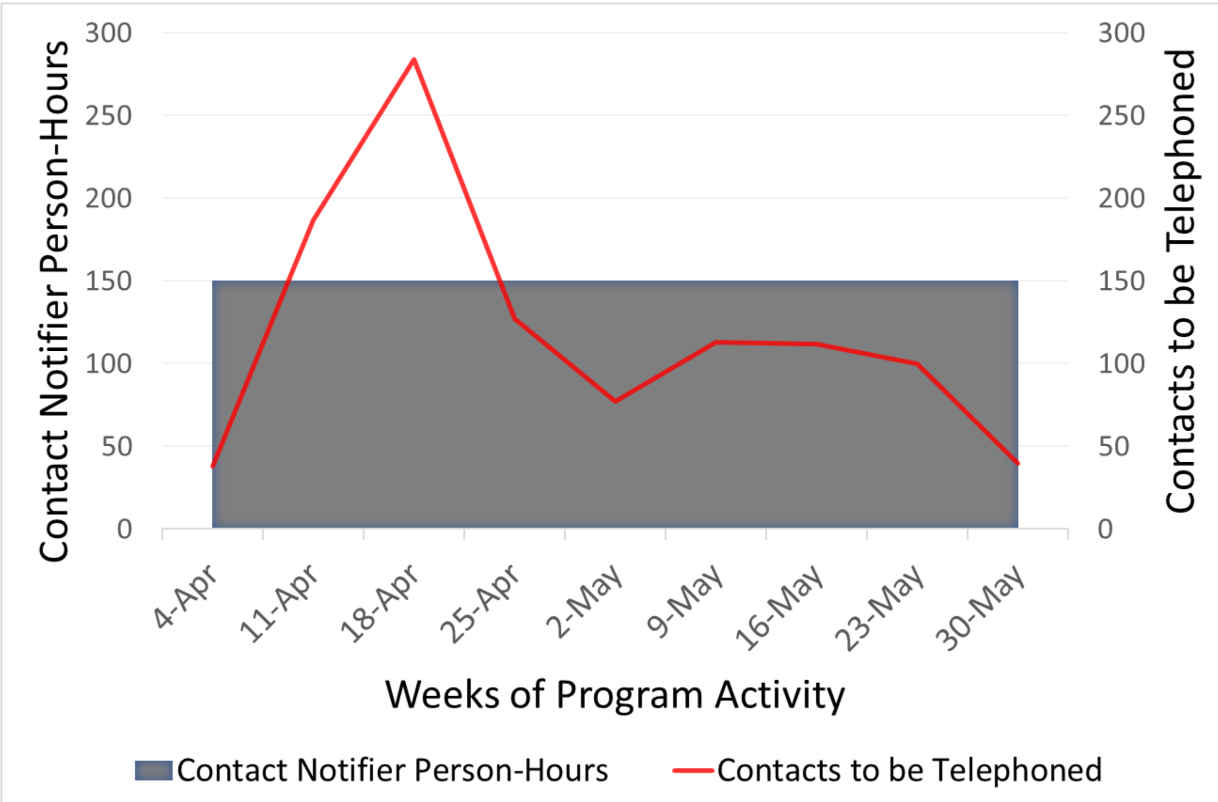
Legend: This conceptual flow diagram illustrates the framework used to define the six key steps (each numbered) of contact tracing. Stepwise yield (Figure 1) for cases is calculated by dividing the number of cases reaching steps #2-#3 divided by the number that made it to the step prior, while stepwise yield for contacts is calculated by dividing the number of contacts reaching steps #5-#6 divided by the number that made it to the step prior. Indicators for cumulative yield (Supplementary Figure 2.2) were calculated by dividing the number of cases reaching steps #2-#3 by the total number of cases reported (step #1), and the number of contacts reaching steps #5-#6 divided by the total number of contacts reported (step #4). Indicators for timeliness (Figure 2.2) were calculated as times between the steps linked by the curved arrows, starting with specimen collection (step #0) and ending with each of the 6 steps (#1-#6). Finally, each of 3 the regression models reported in the Supplementary Tables identify predictors of moving from the previous to the following step**.**

Supplementary Figure 2.2. Cumulative yield indicators for case investigation and contact notification



Legend: Bar graphs showing the cumulative probability of completing the key contact tracing steps of (A) case investigation and (B) contact notification. Probabilities were calculated by dividing the number completing each step divided by the number reported and multiplying by 100. Dotted lines show the percentages lost between processes, calculated by subtracting the percentage completing the subsequent step from the percentage completing the previous step.

Supplementary Figure 2.3: Plot showing supply of and demand for contact notification volunteers[a] over time.



Legend: [a]Contact notification volunteers committed to 5 hours per week, unlike case investigation volunteers who could modify their availability on a weekly basis. Contour plot comparing the supply of contact notifier time (in person-hours, left axis) to the demand for contact notification (in contacts to telephoned per week, right axis) for each calendar week of program activity. New contacts to be telephoned included those with available outreach information who were within 14 days of last exposure to the case and assigned to a contact tracing volunteer). If we assume, conservatively, that an average of one-half hour is required to perform and document contact notification [29], the supply of contact notifier time exceeded demand for contact notification in all weeks.

SUPPLEMENTAL METHODS

Description of Covariates and Reference Groups for GEE models

We included age and gender for both cases and contacts, and race/ethnicity for cases only (this information was not collected from contacts) in the first three GEE models evaluating contact tracing outcomes. We also included contact type (household vs. non-household) and relationship (family, social, work). For categorical variables, we selected the largest category as the reference. Age was categorized into the following age groups (ages all in years): <18, 18-35 (reference), 36-50, 51-5, >65. Race categories included: Hispanic/Latinx (reference), Black/African American, White, Other. Contact types included: household (reference) and non-household. Contact relationships included: family (reference), social, and work. We also used non-male sex as a reference category, which included all females except for two contacts identified as "other" sex without further specification that were only included in the model predicting collection of outreach information. Because public health nurses shared case assignments, we assigned one random intercept to all cases telephoned by public health nurses.

Data Missingness

We determined data to be missing at random based upon (1) lack of identifiable systematic mechanisms leading to data missingness (ruling out *missing not at random*) and (2) observed associations between data missingness and other covariates, as measured via logistic regression (ruling out *missing completely at random)*. Data imputations were performed separately for each model, and the number of imputations was determined by: *(% of missingness) x 100*. The number of imputations for Models 1-3 were 10, 40, and 30, respectively.

Chapter Three. Implementation of a volunteer contact tracing program for COVID-19 in the United States: A qualitative focus group study

Tyler Shelby[1,2¶], Rachel Hennein[1,2¶], Christopher Schenck[2], Katie Clark[1], Amanda J. Meyer[1], Justin Goodwin[1,2], Brian Weeks[3,#a], Maritza Bond[3], Linda Niccolai[1], J. Lucian Davis[1,4,5*], Lauretta E. Grau[1]

¶ These authors contributed equally[*]
[1] Department of Epidemiology of Microbial Diseases, Yale School of Public Health, New Haven, Connecticut, United States of America
[2] Yale School of Medicine, New Haven, Connecticut, United States of America
[3] New Haven Health Department, New Haven, Connecticut, United States of America
[4] Pulmonary, Critical Care, and Sleep Medicine Section, Yale School of Medicine, New Haven, Connecticut, United States of America
[5] Center for Methods in Implementation and Prevention Science, Yale School of Public Health, New Haven, Connecticut, United States of America
[#a] Current Address: Norwalk Health Department, Norwalk, Connecticut, United States of America

This manuscript has been previously published as:

Shelby T, Hennein R, Schenck C, Clark K, Meyer AJ, Goodwin J, et al. Implementation of a volunteer contact tracing program for COVID-19 in the United States: A qualitative focus group study. PLOS ONE. 2021;16(5):e0251033.

[*]*TS's contributions included study conceptualization, data collection and curation, formal analysis, initial drafting and revision of manuscript and tables.*

3.1 Abstract

Background: Contact tracing is an important tool for suppressing COVID-19 but has been difficult to adapt to the conditions of a public health emergency. This study explored the experiences and perspectives of volunteer contact tracers in order to identify facilitators, challenges, and novel solutions for implementing COVID-19 contact tracing.

Methods: As part of a study to evaluate an emergently established volunteer contact tracing program for COVID-19 in New Haven, Connecticut, April-June 2020, we conducted focus groups with 36 volunteer contact tracers, thematically analyzed the data, and synthesized the findings using the RE-AIM implementation framework.

Results: To successfully reach cases and contacts, participants recommended identifying clients' outreach preferences, engaging clients authentically, and addressing sources of mistrust. Participants felt that the effectiveness of successful isolation and quarantine was contingent on minimizing delays in reaching clients and on systematically assessing and addressing their nutritional, financial, and housing needs. They felt that successful adoption of a volunteer-driven contact tracing model depended on the ability to recruit self-motivated contact tracers and provide rapid training and consistent, supportive supervision. Participants noted that implementation could be enhanced with better management tools, such as more engaging interview scripts, user-friendly data management software, and protocols for special situations and populations. They also emphasized the value of coordinating outreach efforts with other involved providers and

agencies. Finally, they believed that long-term maintenance of a volunteer-driven program requires monetary or educational incentives to sustain participation.

Conclusions: This is one of the first studies to qualitatively examine implementation of a volunteer-run COVID-19 contact tracing program. Participants identified facilitators, barriers, and potential solutions for improving implementation of COVID-19 contact tracing in this context. These included standardized communication skills training, supportive supervision, and peer networking to improve implementation, as well as greater cooperation with outside agencies, flexible scheduling, and volunteer incentives to promote sustainability.

3.2 Introduction

The arrival of the coronavirus disease 2019 (COVID-19) pandemic in the US will be long remembered for its suddenness and severity. In the first six months following its arrival in the US [1], there were over three million cases and over 100,000 deaths [2]. As vaccine hesitancy and new viral variants raise the possibility that COVID-19 will become an endemic disease, contact tracing will continue to play a critical role in suppressing local epidemics and lessen the need for stay-at-home orders or other forms of strict physical distancing restrictions. However, the magnitude of the COVID-19 crisis and rate of its spread throughout the US has posed a challenge to implementing contact tracing at the required scale [3]. The high reproductive number [4], lengthy incubation period [5], frequency of pre-symptomatic transmission [6, 7], occurrence of super-spreader events [8], and large proportion of asymptomatic cases [9] have set COVID-19 apart from most other infectious diseases for which contact tracing is used, such as foodborne illnesses [10, 11], sexually transmitted infections [12], tuberculosis [13], and others [14-16]. These, the defining characteristics of the COVID-19 pandemic, have ensured that there would be huge numbers of cases and contacts and a resulting need for extremely large tracing workforces to investigate exposures and interrupt the many chains of transmission [17, 18]. Meanwhile, the lack of feasibility and acceptability of the best alternative, digital contact tracing, has ensured that person-led strategies will likely remain the first-line approach in most settings [19].

In response to these challenges, many states and local health departments rapidly expanded capacity for COVID-19 contact tracing early in the pandemic [20].

Massachusetts, Ohio, Indiana, and Maryland partnered with vendors to facilitate the hiring and management of thousands of new contact tracers, while Washington, Alabama, California, and Tennessee reassigned state employees to this role. Some states such as Rhode Island, West Virginia, North Dakota, and Washington activated their National Guard, and still other states engaged volunteers to fill the role of contact tracers, including Oklahoma, Kansas, Michigan, Arizona, and Connecticut. Learning from prior efforts is paramount given the continued role that contact tracing will play in helping us exit the pandemic.

Implementation science frameworks can aid in systematically identifying and understanding the relationships between factors that influence implementation successes and failures. The RE-AIM framework has been employed extensively for this purpose [21, 22] and contains five dimensions: (1) reach, which focuses on the population an intervention targets and the process of engaging them, (2) effectiveness, which focuses on the intended impact of an intervention and potential barriers to that impact, (3) adoption, which focuses on the setting and individuals delivering the intervention, (4) implementation, which focuses on intervention protocols and strategy, and (5) maintenance, which focuses on intervention sustainability and scalability. Because volunteers were and still are key stakeholders in many contact tracing programs, learning about their experiences is vital for sustaining and scaling up contact tracing. To this end, we conducted focus group discussions (FGDs) with volunteers participating in a contact tracing program in Connecticut. We sought to characterize their perspectives and experiences using the RE-AIM framework in order to understand facilitators of, barriers to, and potential solutions for improving implementation.

3.3 Methods

This qualitative study was part of a larger multiple methods evaluation of a volunteer-driven contact tracing program established in a partnership between the New Haven Health Department, hereafter referred to as the "Health Department", and Yale School of Public Health (YSPH) in March 2020. We report our methods below in accordance with the Consolidated Criteria for Reporting Qualitative Research (CO-REQ).

Setting and Procedures

New Haven is home to nearly 130,000 residents and is part of the New York Metropolitan area. The Health Department established a partnership with Yale University for volunteer contact tracing on March 27, 2020, as previously described [23]. Briefly, over 150 volunteer students, staff, and faculty from Yale's public health, medical, physician assistant, and nursing programs participated in the program. Volunteers began making contact tracing calls on April 4, 2020, prior to New Haven's initial peak of COVID-19 cases around April 21 [24]. In mid-April, the Health Department assigned 40 public health nurses to assist with contact tracing. By mid-May, the program had responded to over 2,000 lab-confirmed cases of COVID-19.

Volunteers worked remotely and were divided into two teams. One team ("case investigators") interviewed cases to identify contacts and counsel self-isolation, while the other team (“contact notifiers”) notified contacts about their exposure to COVID-19 and recommended self-quarantine. The case investigation team was supervised jointly by the Health Department and YSPH, and the contact notification team was supervised by YSPH faculty and staff. Volunteers participated in a one-hour, virtual training session on contact tracing that covered US Centers for Disease Control and Prevention (CDC) guidelines [25], local case- or contact-specific protocols for implementing contact tracing, and regulations for protecting confidentiality. All case investigator volunteers received training on basic communication and interviewing skills, except medical students who all had prior training in this area. Volunteers used email and GroupMe (Microsoft, New York, NY), a mobile group chat application that hosts discussion threads, to communicate with supervisors or other team members as needed.

Each day, the Health Department’s lead epidemiologist identified new positive COVID-19 cases from the state’s reportable disease database and shared their corresponding outreach information with the case investigation team. Case investigators used New Haven’s existing emergency management software (Veoci, New Haven, CT) to record call attempts and responses to the interview questions. The case investigator team shared a daily list of reported contacts, without any information regarding their respective cases, with the contact notification team via email. This team then used a free-text template (Microsoft Word, Redmond, WA) to record notes and outcomes of call attempts to contacts. These data were then entered into a master spreadsheet (Microsoft Excel, Redmond, WA) by volunteers assigned to data management tasks. Case investigators routinely asked cases about food or housing insecurities, ability to isolate within homes, access to medical care, and other social needs, while providing numbers to local support organizations or free clinics when applicable. Contact notifiers also provided links to resources when applicable but did not routinely assess contacts for the same needs. Team leads communicated changes in guidelines and protocols to volunteers via email and modified data collection forms appropriately.

Eligibility and Recruitment of Volunteers

Eligibility criteria included being a volunteer in the case investigation or contact notification teams. We excluded the less experienced case investigators, defined as being in the lowest 25th percentile of total case assignments (<7 assignments). We did not exclude any contact notifiers because all assignments were distributed equally among this team, whereas case investigators were able to adjust their availability each week. We emailed invitations to all eligible volunteers to participate in the study. We set an initial recruitment goal of 18 participants from each team based on estimates of the number of focus groups required for thematic saturation [26]. We enrolled participants consecutively until the target sample size was reached, ensuring balanced representation of volunteers from different schools and university positions (i.e., students, faculty, and staff).

Data Collection

Three members of the research team (TS, a male MD/PhD student; KC, a female research associate with a master's degree in public health; LG, a female social scientist and faculty researcher with a doctorate in psychology) conducted the focus groups. KC and LG led the case investigation discussions as moderator and scribe, respectively. TS and LG led the contact notification discussions, each serving as moderator or scribe. All had previous training or experience in conducting qualitative interviews. Because several participants knew TS as a fellow student and volunteer assistant coordinator of the case investigation team, he participated in the contact notification FGDs only. All participants were informed at the start of the discussions of the researchers' role in evaluating the volunteer contact tracing program. The FGDs were held via videoconferencing (Zoom, San Jose, CA) and conducted separately for case investigators and contact notifiers. The semi-structured FGD guide (Supplementary Text 3.1), developed around our primary purpose statement, included four domains: 1) experiences volunteering with the program, 2) successes and challenges related to contact tracing activities, 3) training and unforeseen experiences, and 4) perspectives on how to improve and sustain the program. After each FGD, participants received a follow-up survey inviting them to provide demographic information and any additional thoughts or comments they had.

We transcribed session recordings using an automated transcription service (Trint, London, United Kingdom). Additional researchers (AM, RH, CS) reviewed transcripts for accuracy against the audio and video recordings. Two moderators (TS and LG) iteratively assessed the content of case investigator sessions until no new themes emerged (i.e., saturation had been reached), and separately followed the same process for contact notifier sessions [26]. We did not conduct follow-up interviews or discussions and did not have participants review the transcripts.

Analysis

The coding team (TS, RH, LG) independently reviewed one case investigator and one contact notifier transcript and met to discuss and develop the codebook inductively. They discussed and resolved all coding discrepancies by consensus. Once acceptable inter-coder agreement [27] was reached, TS and RH divided the remaining transcripts and free-text responses from the follow-up surveys between themselves for independent coding. The full coding team continued to meet regularly to resolve any remaining coding questions. The coding team initially used Microsoft Word for coding, and the data were subsequently entered into ATLAS.ti (Version 8, Berlin, Germany) and analyzed iteratively using thematic analysis [28]. Study participants did not provide feedback on the findings.

After the themes had been identified, we used the RE-AIM framework [21, 22] to deductively organize emergent themes. We assigned themes related to contacting and engaging clients to the reach dimension, challenges to achieving public health outcomes (i.e., isolation for cases and quarantine for contacts) to the effectiveness dimension, volunteer delivery of the intervention and the setting in which they operated to the adoption dimension, and feasibility and acceptability of the program to the implementation dimension. The final theme concerning the sustainability of a volunteer-driven contact tracing program was assigned to the maintenance dimension. Once organized according to the RE-AIM framework, we identified specific barriers, facilitators, and solutions within each RE-AIM dimension.

Ethics Statement and Consent Procedures

The study protocol was approved by the Yale Human Subjects Committee (Institutional Review Board Panel A for Social, Behavioral, and Educational Research) and the New Haven Health Department. A waiver of written consent was approved by the Human Subjects Committee because the study posed no greater than minimal risk and did not involve any procedures that would require written consent in a non-research context. Before video-recording the session, the group facilitators read the consent form aloud and obtained verbal consent from all participants to be in the study and be recorded.

3.4 Results

Characteristics of the Study Sample

At the time of study recruitment, there were 106 case investigation volunteers and 36 contact notification volunteers involved in the program. We emailed 83 eligible volunteers from the case investigation team and 36 from the contact notification team, excluding 23 case investigators who made too few calls. We consecutively enrolled all participants who replied to the initial recruitment emails, sending reminder emails until we recruited a sample of 18 participants from each group. The six FGDs (three with case investigators and three with contact notifiers) ranged from 73 to 85 minutes in duration and occurred May 6-12, 2020. Six participants attended each session. Table 3.1 describes the sample characteristics. School affiliations within the sample were similar to the those on the volunteer team overall, with a slightly lower representation of nursing students and a higher representation of faculty and staff in the study sample.

Table 3.1: Participant Characteristics

Characteristics	Case Investigators (n=16) * n (%)†	Contact Notifiers (n=17) * n (%)†
Age, median years (Q1, Q3) §	28 (27, 29) §	25 (22, 28) §
Female	12 (75)	14 (82)
Race/Ethnicity		
Non-Hispanic White	12 (75)	13 (76)
Asian	3 (19)	1 (5.9)
Hispanic/Latinx	1 (6.3)	3 (18)
University Affiliation*		
Public Health Student	6 (33)	16 (89)
Medical Student	9 (50)	0 (0)
Nursing Student	1 (5.6)	0 (0)
Post-graduate	1 (5.6)	0 (0)
Faculty / Staff	1 (5.6)	2 (11)
Bilingual¶	3 (0.19)	3 (0.18)

Legend. ******Only 33 of the participants completed the follow-up demographic surveys, thus demographic and language information about three participants is not included in this table. University affiliation was available for all participants.*

† *Unless otherwise specified*

§ *Median (quartiles 1 and 3)*

¶ *Conducted interviews/notifications in Spanish in addition to English*

Identified Themes

We identified 12 themes across the five RE-AIM dimensions. There were no differences in themes expressed by volunteer type or by participant demographics or between the FGDs and follow-up free-text surveys.

Reach Dimension

We identified two themes, Making Contact and Establishing Rapport, under the reach dimension. These captured volunteers' experiences attempting to get in touch with and engage the target population.

Making Contact Theme

Participants detailed their experiences calling and attempting to reach cases and contacts and described the challenges they faced with this early step of the contact tracing process. They noted the difficulty in getting the target individuals to answer their calls and reported that it was rare for their unanswered calls to be returned. However, some succeeded by either leaving voicemails or using text messaging in addition to voicemails.

> *"The hard part is getting them on the phone in the first place, to answer the phone or return the voicemail." (Participant 1:6, Case Investigator)*

> *"When they don't have [a voice mailbox], I've just been sending them a text with information from the callback scripts. I don't know whether that is appropriate or inappropriate, but I felt that that would be how I would want to get the information." (Participant 5:1, Contact Notifier)*

Several also noted that calls made in the afternoon or evening were more likely to be answered than those made in the morning.

> *"I found that a lot of cases don't like being called in the morning. As I started, I would call at 9:00 or 10:00 in the morning, cause I just felt like maybe that would be a reliable time to get people and was also convenient for me. More than once I was basically told [by cases] 'don't call before noon.' So, I no longer call before noon." (Participant 1:5, Case Investigator)*

Establishing Rapport Theme

Volunteers repeatedly emphasized the importance of engaging with clients authentically. Participants felt that finding the most convenient times for the conversation, showing empathy, and addressing sources of mistrust were effective in building trust and rapport. Some volunteers developed these approaches by drawing on prior experiences in patient care or other client-related work, while others did so by trial and error.

> *"I've personally gotten a few of those calls where they don't appreciate the call. They don't want to talk to you. It's been interesting [figuring out] how exactly do you handle those, because at first, I was really nervous making those calls but now it's been a lot more natural and it's been a very interesting process, kind of learning how to do that." (Participant 6:5, Contact Notifier)*

> *“I think that's why it's so critical to have been in the health care profession beforehand, because a lot of these questions are very sensitive, and you have to kind of know how to deal with that and make it okay. So, I would say yeah, training through med school has helped.” (Participant 1:2; Case Investigator)*

Some call recipients seemed suspicious of callers, and participants occasionally felt “awkward” trying to convince these individuals that they were authorized representatives of the Health Department. Others described the process of eliciting information about contacts from cases as particularly difficult because many cases either felt uncomfortable providing or simply did not know the necessary information about their contacts. One participant stated that a few cases disclosed their status as undocumented immigrants and were fearful about providing information about themselves or their contacts. Despite these challenges, participants stated that most cases and contacts appeared to be “very receptive” to providing information and following the recommended guidelines.

> *“People are very guarded about who's in their house...But I think half the time it's the person. They're just a little bit wary. And half the time it's just the situation. Like, they would love to tell you, but they're also scared. And the other portion of the time people are just really open and they're trusting and then it's not a big deal.” (Participant 1:2, Case Investigator)*

Effectiveness Dimension

We identified two themes within the effectiveness dimension, Delays and Community Needs. Both concerned barriers to achieving the desired outcomes of isolation for cases and quarantine for contacts.

Delays Theme

Participants discussed several types of delays that prevented them from reaching cases and contacts within an epidemiologically relevant timeframe. There were delays in receiving test results and delays when a volunteer could not speak the client's preferred language, requiring reassignment to a volunteer proficient in the preferred language on the following day. These delays sometimes resulted in reaching contacts after the two-week window for effective quarantine had expired. Others described the frustration of reaching contacts only to discover that they had already been diagnosed with COVID-19.

> *"We have no idea when things are getting reported to the state, when the state then goes to the city, when the city forwards that result along to our coordinators, and then when they finally put it on our list…there are some health clinics that seem to be slower reporters." (Participant 1:5, Case Investigator)*

While some delays in the overall contact tracing process were beyond the control of the program, such as cases choosing to delay seeking COVID testing or slow reporting of test results, participants felt that identifying cases in need of translators before the first call was an actionable way to prevent additional delay.

"I know that they're pulling the data from the state database but having a flag for language would really cut down in terms of time, because we're talking about an extra 24 hours." (Participant 4:1, Case Investigator)

Community Needs Theme

Even when reached in time, participants stated that many cases and contacts indicated that they were either experiencing or expecting difficulties in adhering to isolation or quarantine recommendations. These challenges stemmed from job or wage loss, difficulties providing food for themselves or their families, and for some, a lack of housing. Participants observed that these challenges occurred more frequently among contacts from Hispanic communities and that contact tracing calls provided a unique opportunity to identify additional needs for support or resources.

"I had one case or contact that I called, and they said, 'There's no one else in my house who can get groceries. I'm the only one who can go out. I don't know how we're going to get food. My husband is very sick and I'm trying to take care of him.'" (Participant 4:5, Contact Notifier)

"When I speak to Spanish-[speaking] contacts...what I hear more often is, 'I can't not go to work.' And I don't hear that as much when I [call] other contacts that I receive. I just hear people panicking essentially over the phone." (Participant 5:5, Contact Notifier)

Participants appreciated that the Health Department instructed volunteers to routinely assess these needs and thought many cases and contacts viewed this needs assessment as a sign of the city's concern for its residents. However, some participants were unsure whether these needs would ultimately be addressed by the city and questioned the utility of assessing needs when they could offer cases and contacts little assurance that the needs would be satisfied.

> *"The other thing that was added actually fairly recently was [a prompt asking if] they have a need for housing support, food support, financial assistance, any of those things…it just adds a human element to the interview because, by asking that, it shows that we're not only doing this to use the participants as a source of information, but also we're here because we care about them as part of the community. So, it adds that element that I think people are very receptive to." (Participant 2:2, Case Investigator)*

Adoption Dimension

We identified five themes that fit under the adoption dimension: Volunteer Motivations, Time Management, Knowledge, Skills, and Collaborative Learning. They addressed the dimension's focus on the individuals delivering the intervention (e.g., what their motivations were for volunteering); the time, knowledge and skills required of those individuals; and key characteristics of the setting in which they functioned.

Volunteer Motivations Theme

Most participants reported a strong desire to help their community combat the COVID-19 pandemic. The effects of the pandemic had simultaneously suspended in-person classes, clinical training, and routine work, leaving participants feeling idle and powerless. The contact tracing program offered a chance to respond to the pandemic by applying their knowledge and skills as budding or established practitioners, teachers, or researchers in the health sciences. Some noted that the safety of being able work remotely made telephone contact tracing more attractive than other volunteer opportunities that required physical interaction.

> *"As someone who's going into this field, I've always wanted to do outbreak investigation and outbreak response kind of stuff. And it was really hard to feel powerless. And so, when this opportunity came up, I was like, this is something that I can do, like using my education and my skills." (Participant 4:1, Contact Notifier)*

> *"I heard about this [volunteer opportunity] and how it could really use the skill sets of people who are trained to interview patients. And I thought that was one of the best ways I could help." (Participant 1:3, Case Investigator)*

Time Management Theme

Balancing contact tracing duties against other responsibilities was easy for some yet challenging for others. Unpredictable schedules, especially for students during examination periods, made it difficult for some to keep up with their tracing responsibilities. Case investigation volunteers were allowed to adjust their assigned case load every week to match their availability and used this flexibility to better manage their time and level of involvement. In contrast, contact notification volunteers were given fixed case assignments on a rotating basis and noted that their inability to control their workload could be stressful.

> *"It's really hard to just get an email all of a sudden [that says] 'you have to call this person within 24 hours.' And I wasn't able to do all of them in the right timeframe because of that. I had too much other work to do." (Participant 6:2, Contact Notifier)*

In addition, participants from both teams reported that the sporadic workflow was challenging. Many said that they felt out of practice making calls after even a few days' hiatus, while others felt "burnt out" after making many calls in a short period.

> *"I think the issue is just that the current inconsistency of not being as well-practiced in the ability to do the interview as well as you might have been doing them when you had a more consistent stream of calls." (Participant 2:1, Case Investigator)*

> *"I found that if I was doing this for four hours a day, I got kind of pretty burned out by it... the next day I was like, I don't want to do this." (Participant 2:4, Case Investigator)*

Knowledge Theme

Participants highlighted the importance of knowing and effectively applying current CDC COVID-19 recommendations and other policies regarding confidentiality and privacy protection. Because the tracing scripts changed frequently during the early phase of the pandemic to meet the changing CDC guidelines, participants found it challenging both to stay current and to feel confident that they were providing accurate guidance to cases or contacts in every situation.

> *"[CDC guidelines] are very fuzzy and always evolving in terms of the recommendations. That makes it really hard to feel confident in what we're telling people." (Participant 2:2, Case Investigator)*

They also often found privacy protection policies difficult to apply due to the unique circumstances of each call. Participants said they were often required to speak with family members or other proxies in tense or emotional circumstances when cases or contacts were severely ill or unavailable to speak. A lack of familiarity with navigating and applying privacy policies within these unpredictable scenarios made it difficult for some participants to discern how much information they could appropriately share with proxies.

> *"More information on [privacy and confidentiality], who we can and cannot tell certain things to, how to deal with proxies. I think that would have been really helpful." (Participant 3:3, Case Investigator)*

In addition, participants occasionally struggled to answer questions from cases about why certain data, such as information about contacts (name, phone number, age, gender) or current health status, needed to be collected. On the other hand, contacts frequently questioned where callers obtained such information. Participants believed that cases were hesitant to provide information when they were unsure what the city would do with it or thought that it would intrude on the privacy of their contacts. Although the importance and utility of each part of the script was covered in the volunteer training, participants felt that providing refresher sessions or opportunities to clarify how data would be used could have increased their ability to adequately answer case and contact questions in order to better promote faith and trust.

> *"People would ask 'well, why do you need the information from my husband's phone number? He's here. He's listening to this conversation. He knows that I have COVID and that he's been exposed to COVID. So now I need to give the health department his phone number [so] that someone else can call him and tell him that I have COVID?' or, similarly, they'll say, 'Oh, everyone knows. I've told [my close contacts]. So why do I need to [give you their number]? They wouldn't want me giving [their phone number] so that you can bother them.'" (Participant 2:2; Case Investigator)*

> *"I got a lot of 'where's this data [personal data about the individual] coming from, where are you getting this information?' And I think it would have been helpful to have known exactly where that information was coming from so that I could have a better answer for that." (Participant 6:2, Contact Notifier)*

Skills Theme

All participants strongly agreed that effective communication skills were critical to establishing rapport with those facing a new and potentially frightening illness. Many adapted the interview script to this end. For example, rather than starting with standardized questions about demographics and specific symptoms, several participants found that beginning by asking open-ended questions about the client's current situation and setting expectations about content and length of the call helped engage some individuals.

> *"I do a little bit more signposting in the interview than is included in the script. What I mean by that is setting an expectation about what are what are all the things we're going to talk about...I've found that sometimes cases are surprised by how long [the interview] is going, that they start to check out a little bit. Whereas if the expectation is very clear from the get-go, then I think people let their guard down a little bit and also just feel a little bit more comfortable with the interview." (Participant 1:5, Case Investigator)*

Applying techniques to communicate effectively and adapting messages in real-time was especially critical during moments of high emotion or conflict. For example, volunteers described unexpectedly being the first to inform cases about their positive test results or learning from those answering that the case had died or speaking to individuals who did not wish to participate. In one instance the participant had felt obligated to call 9-1-1 for emergency medical assistance for a case who was in physical distress. As discussed below, participants repeatedly suggested that role-playing exercises be included in their training to build skills and confidence in navigating these emotionally charged or unanticipated situations.

"In the training, I [would] definitely [add] like a role player, an initial call, for both a standard case and a nonstandard case. So, for instance, I've had a call where someone just started swearing at me on the phone, which is not something you expect and then I had another call where I had to call 9-1-1 on that person's behalf… So, I think, because we're calling sick people, getting [new trainees] ready for what a normal case looks like and what an abnormal case looks like, or just to get them able to think on their feet, would probably be important." (Participant 1:4, Case Investigator)

Collaborative Learning Theme

Participants frequently mentioned a need for internal communication structures to better promote information exchange, shared learning, and timely adaptation to periodic changes in guidelines or programmatic priorities.

Having direct communications with program supervisors was very important to participants, and they especially appreciated quick responses to their questions. They felt it was important for supervisors to communicate changes in CDC guidelines and programmatic priorities, as well as to be responsive to volunteers' concerns, suggestions, and requests for changes or clarifications in protocols. These "two-way communications" were viewed as critical to maintaining "morale and faith" in the mission and promoting team solidarity. They described the chat application GroupMe as being "so helpful" in providing a direct mechanism to reach the supervisors with questions and view other volunteers' comments. However, several participants also noted that discussion threads were often basic and repetitive, reducing their value.

> *"[The leaders] have been really responsive if I send the GroupMe message. People are pretty happy to respond, and they do that very quickly. That's been good." (Participant 3:2, Case Investigator)*

> *"I am on the GroupMe, I've been on it for since I started, but I basically ignore it because there's so many messages that go into it and so many of them are, 'so I'm a new volunteer, how do I use [the interview software]?' And then it's a 20-message thread and everyone has to see it. So I check it like every few days and I just kind of scroll through." (Participant 3:6, Case Investigator)*

While the messaging app served as a useful hotline to request help from supervisors, many felt that other mechanisms were needed to provide peer-support, foster community, and learn from the experiences of their peers. Several mentioned that they thought that hearing about other volunteers' thoughts and experiences during the FGDs had been helpful. They advocated establishing a "buddy system" or regular meetings with small groups of peers for volunteers to share experiences, learn from one another, and debrief after difficult calls. They felt that such meetings could help to provide regular updates on changing protocols as well as promote a sense of community in an environment where in-person interactions were impossible.

"At the moment I feel very comfortable doing a few practice calls with someone who's just starting, going through some of the situations I've been through, a regular one, a few difficult ones and literally spending 20 minutes, half an hour doing those things. If someone had done that for me at the start, I would've felt a lot more comfortable than I originally did." (Participant 5:1, Contact Notifier)

"I don't think that I necessarily need more training, but the GroupMe, [or] having a short meeting once a week with small groups to discuss newer things I think would be helpful." (Participant 4:2, Contact Notifier)

Implementation Dimension

Two themes emerged that concerned the implementation dimension: Tools and External Coordination. Each focused on key aspects of the feasibility of implementing a volunteer-based contact tracing program.

Tools Theme

Participants described several tools that were essential to their tasks, and the one most frequently discussed was the script. Many thought it was difficult to deliver the words verbatim because doing so made them sound "like a robot." As previously noted, many adapted the script language or individualized their introductions in an attempt to rectify this problem. However, when asked if replacing the script with a bulleted list of objectives would be preferable, most said that a word-for-word script was necessary as a training aid, especially during a tracer's first few calls. Other useful tools that participants regularly consulted included guidance documents provided by the program and a list of frequently asked questions. Participants appeared enthusiastic to add to and update these materials based on their own experiences. Some even suggested compiling examples of challenging call scenarios and response strategies into a reference document.

> *"I don't think [any] amount of training can really prepare [you] for that first call. I know that sounds, I mean, yes, there was training to prepare for the first call, but I think you'd need that script just as that safety net." (Participant 5:2, Contact Notifier)*

> *"It would be helpful to have a repository of what these possible [call scenarios] are based on experience, real experience, and we could all contribute to that." (Participant 1:2, Case Investigator)*

Participants also identified a need to adapt scripts and protocols for asymptomatic cases, minors, non-English speakers, and cases residing in congregate settings such as nursing homes. Calls to individuals in congregate settings were especially challenging to navigate because cases were often severely ill or otherwise incapacitated, caseloads were high, staff were already overwhelmed and overloaded with calls, and other factors. These cases were redirected to the Health Department for follow-up.

In addition to these specific contexts, participants felt that the contact notification process should be modified for members of a case's household and offered examples to support this suggestion. First, cases were often reluctant to provide information about their family members, possibly due to mistrust of the caller, fatigue and annoyance from being called by multiple agencies, or a desire to prevent additional calls to their household contacts. Second, even when this information was successfully collected by case investigators, they stated that it could be "a bit of a puzzle" to correctly identify cases and contacts at the beginning of a call without compromising privacy. When incorrect assumptions were inadvertently made or participants found themselves duplicating a call because a case had given the same phone number for multiple contacts (*e.g.*, phones shared within households), participants on the contact notification team said the calls felt like "a mess" and that they lost credibility with the contacts. Last, participants often struggled to identify a single exposure date for contacts who were living with a case and hence continuously exposed, whereas it was simpler to identify a discrete date for non-household contacts. All these experiences led volunteers to recommend conducting household contact notification together with the case interview.

> *"There should be a separate [protocol] for household contacts. A household contact represents an ongoing exposure dynamic that is different than non-household contacts. If possible, the person calling the cases should contact the household contacts." (Participant 4:2, Contact Notifier)*

Data entry software was also identified as a critical contact tracing tool. Many case investigator participants appreciated the flexibility of New Haven's emergency-management software, as it allowed them to scroll through the questions and enter data in a smooth yet flexible order. This feature was highlighted as important when interviews did not follow the planned order of questions. With regard to data management, however, the free-text data collection tools used by the contact notification team were challenging to process, and several participants responsible for entering these data felt that they "should be updated" and recommended the use of a standardized form. Another tool that volunteers discovered to be helpful was dialer software (Doximity, San Francisco, CA) to mask their personal information, display the Health Department's phone number or a leave a virtual callback number (Google Voice, Mountain View, CA).

> *"So, the number they see on their caller I.D. is from the [health department]… And then the number we leave [for] voicemail is my Google Voice number that will forward to my cell phone. So, they don't know who we are, they don't have our name or our personal information any more than what we say in the voicemail." (Participant 1:4, Case Investigator)*

External Coordination Theme

Participants from both teams spoke often about how the activities of external organizations affected their own activities. Cases and contacts often reported receiving numerous calls from various organizations, such as healthcare providers, testing facilities, and insurance companies, and were often "annoyed" at hearing the "same things from multiple different people." In some instances, different organizations provided conflicting advice about isolation and quarantine periods. Ultimately, these experiences often led to call recipients being less receptive to engaging with the caller, thereby making it more difficult to collect the necessary information.

"When there are multiple people who are giving [the case] recommendations that are not the same, it becomes challenging to feel like you are authoritative and for people to feel like they know what's going on." (Participant 2:4, Case Investigator)

"Because they've tested positive, their doctor has given them a lot of recommendations already and they're hearing it from us again...I think lately I've been getting more people who've tested positive and they've been annoyed with my call, more so I think because they've heard kind of the same things from multiple different people." (Participant 5:4, Contact Notifier)

Maintenance Dimension

The final theme, Sustainability, focused on long-term threats to the volunteer-driven contact tracing program and aligned well with the *maintenance* dimension of RE-AIM.

Sustainability Theme

Several participants considered a volunteer-driven workforce as ideal for the "crisis phase" of an epidemic, allowing an accelerated response without the delays inherent in formal hiring or when re-assigning existing employees to contact tracing was not possible. However, participants did not see a volunteer-driven program as sustainable during the "maintenance phase" following the crisis. Some participants had recently graduated and were departing for jobs or further training, and others planned to soon return to class or to other responsibilities.

"I think that you just unfortunately have to account for the fact that [volunteers] who are trained might be gone two months later and then [training and volunteer turnover] keeps going on and on again." (Participant 6:6, Contact Notifier)

As nearby states began hiring and paying contact tracers, other volunteers reported feeling frustrated, underappreciated, or less inclined to continue with the program. Participants suggested several strategies to maintain long-term involvement of contact tracers such as hiring them into part- or full-time paid positions or incentivizing student volunteers by offering academic credit for their work.

"I think it's a great idea for an acute crisis emergency for those first few weeks. Now this is an ongoing thing, I feel putting in a long-term solution, and maybe this counts as a practicum for the incoming students or for the continuing students or finding a way you can either weave this into the program... [or] They should be paying us to do it, not exorbitant amounts. But like 10 or 12 dollars an hour...I think that not doing that is a real disservice." (Participant 5:1, Contact Notifier)

Synthesis of Barriers, Facilitators, and Proposed Solutions across Themes and RE-AIM Dimensions

Table 3.2 summarizes the facilitators, barriers, and potential solutions for improving implementation of contact tracing as reported by participants, mapped to their respective themes, and synthesized within the RE-AIM dimensions.

Table 3.2 Summary of findings organized by themes within the RE-AIM dimensions

Dimensions	**Themes**	**Facilitators**	**Barriers**	**Potential Solutions**
Reach	Making Contact	Dialer software used to replace caller's personal phone number with a health department number	Low answer rate	Introduce text messages to introduce phone calls; obtain outreach preferences at testing
	Establishing Rapport	Dialer software used to replace caller's personal phone number with a health department number	Lack of trust in an unknown caller	Routinely address privacy concerns
		Many cases and contacts willing to participate out of a desire to help their community	Low public unawareness of contact tracing leading to lack of interest or comfort in providing information about contacts	Organize public awareness campaigns; provide thorough explanations for why contact tracing is important for the community
Effectiveness	Delays	--	Late reporting of test results	Automate test reporting and transfer of information to contact tracers
			Unknown language preferences	Verify language preferences at point-of-testing
	Community Needs	Health department routinely assesses needs as part of outreach	Lack of money, or adequate food & housing to help cases to adhere to isolation & quarantine	Increase funding for financial, nutritional, and housing supports; educate tracers about how such needs can be met
Adoption	Volunteer Motivations	Partnerships with academic institutions and students	--	Reward non-employed tracers with academic credit or certificates of experience
	Time Management	Weekly availability survey used for case investigation team	Shifting volunteer availability	Offer flexible, volunteer-driven scheduling
			Inconsistent workload due to varying case incidence with skill loss from inactivity	Ensure consistent baseline involvement with longitudinal skill refreshers

	Knowledge	Brief, targeted training provided to new volunteer tracers	Need for broad mastery of diverse content areas including biology, guidelines, procedures	Offer self-directed, online training modules to obtain baseline and knowledge
		Many volunteers had previous education or experiences in health sciences	Frequent changes to guidelines due to evolving understanding of COVID-19 transmission dynamics	Frequently revise protocols to reflect changing guidelines, and rapidly communicate of these changes to the tracers; provide repository of call scenarios for training
	Skills	Many volunteers previously trained in patient communication skills	Need for effective communication skills for building rapport	Incorporate role-plays and simulations to build up communication skills during training
	Collaborative Learning	Leaders regularly responded to questions by e-mail or GroupMe*	Lack of communication with leadership and feedback to ensure quality performance	Integrate two-way communication via messaging apps, email, and supervisory support
			Sense of isolation and lack of community while working remotely	Encourage peer mentorship, buddy systems, and regular, small-group peer meetings
Implementation	Tools	Software was flexible and allowed case investigators to adapt it to the interview at-hand.	Impersonal, non-conversational script	Personalize script and allow for adaptation to the clients' needs.
			Lack of interoperability of electronic systems	Provide simple and standardized data collection tools
		Health department adapted script according to volunteer suggestions	Loss of volunteer privacy	Offer and/or require use of call masking software
			Need for specialized protocols for key populations†	Develop and apply specialized protocols
	External Coordination	--	Duplicate calls to the same cases or contacts, leading to frustration and decreased engagement	Coordination with other clinics, laboratories, and health organizations to streamline and integrate communication
Maintenance	Sustainability	--	High volunteer turnover; decreasing motivation over time	Offer payment or other compensation and acknowledgement such as academic credit or certificates of experience

Legend: *Mobile app for hosting chat-groups; †Asymptomatic cases, residents of congregate settings, minors, non-English speakers, household contact

3.5 Discussion

This is among the first studies to comprehensively describe the implementation context of COVID-19 contact tracing and provides a unique window into the rich experiences and perspectives of volunteers involved in a high-volume program at the peak of the April-June 2020 surge in the northeastern US. We identified many barriers to delivering this complex intervention in the midst of a public health emergency, but also several facilitators and many potential solutions for improving implementation, both in general and in the context of a volunteer program. Many insights echo the prior literature on contact tracing for other diseases, while others remain unique to the context of COVID-19 and the crisis scenario of a rapidly emerging pandemic. Categorizing our findings according to the RE-AIM framework allowed us to group many disparate themes into discrete, well-validated dimensions for improving implementation [21, 22].

The reach and effectiveness of COVID-19 contact tracing vary across settings, with proportions of cases successfully interviewed ranging from 53% - 99% [29, 30] and adherence to self-isolation instructions reported as low as 25% [30]. While the specific mechanisms driving these outcomes are not yet fully understood in the context of COVID-19, challenges to the reach and effectiveness of contact tracing in other settings have been associated with several client factors including anticipated stigma and loss of privacy [31-34], language barriers [31], and low public awareness of the importance of contact tracing [31, 33, 35, 36]. The apparent reluctance to answer our participants' calls may relate to several of these barriers. The RE-AIM framework suggests that COVID-19 contact tracing programs might consider engagement strategies to enhance uptake such as using the initial point-of-testing interaction to identify optimal times to call and to document language preferences, and possibly using text messaging to identify and introduce outreach workers prior to calling. Our participants also highlighted the role of financial, nutritional, and social supports for those expecting or disclosing difficulties with isolation or quarantine as another way to potentially enhance the impact of contact tracing. Similar supports are commonly provided to tuberculosis cases to enhance patient outcomes and acceptance of contact tracing [37]. This notion is further reinforced by a recent anonymous survey study conducted in the UK which found that increased adherence to COVID-19 self-isolation and lockdown instructions was associated with having received help from anybody outside of the household [30].

A shortage of human resources is a major challenge to adoption of contact tracing for COVID-19 and other communicable diseases [31, 33, 38-41], both because many contact tracers are needed and because this capacity must be flexible enough to expand and contract with the waves and surges of the epidemic. In addition, as noted above, outreach workers must have good communication skills and a detailed knowledge of program policies and guidelines [35, 38, 42, 43]. Engaging/hiring volunteers is one option for rapidly scaling a pandemic contact tracing workforce [44] and was a strength identified by our study participants. There are also several personal benefits that might be highlighted to attract volunteers to such a workforce, including the anticipated satisfaction of contributing to the pandemic response and opportunity to gain practical experience in a health science field. Yet several challenges to a volunteer-driven workforce remain, such as managing shifting schedules and training lay persons from diverse backgrounds to act as public health agents. Allowing volunteers some degree of flexibility in their scheduling may allow programs to accommodate volunteers' external responsibilities, while using self-directed, online training modules [45] would decrease the initial training burden on local programs and allow them to focus their efforts in this area on ongoing education about local guidelines and practices, and on skill-building exercises such as role plays.

Another important insight from our participants about adoption of a volunteer contact tracing model included their suggestion to create a learning community to help them overcome their relative inexperience with outreach work. In other settings, pairing new trainees with those who are more experienced and/or facilitating an environment in which trainees can learn alongside their peers and support one another has been shown to increase trainee confidence and skill [46]. This sense of community seemed particularly important in the context of COVID-19 when requirements to work remotely made it more difficult to learn new skills because it was harder to receive feedback from peers or supervisors. We strongly recommend that COVID-19 contact tracing programs develop and promote robust communication and support structures within their organizations, using strategies such as peer-mentorship and regular, small-group meetings.

Within the implementation dimension, we found that properly designed tools for data collection and storage, specialized protocols for key populations, and coordination with external organizations were thought to be critical to success. These implementation factors may also have positive spillover effects for adoption, reach, and effectiveness in that efficient, user-friendly, non-redundant systems benefit call recipients and contact tracers alike. Two simple suggestions for improving efficiency included adopting more accessible tools for data collection and management, as shown with contact tracing for other diseases [33, 38, 39, 41, 47], and coordinating case and contact interviews within the same household as is commonly done in tuberculosis contact investigation [48, 49]. A threat that participants identified, poor inter-agency communication, has also been described during tuberculosis contact investigation in border regions [39]. In contrast, close coordination of Ebola contact tracing teams led to faster and greater uptake in the target populations [33, 50]. Further benefit was realized by these response teams when they integrated services across disciplines, including social supports for basic needs and mental health, information-sharing with local community leaders, and public health interventions including active case-finding and quarantine. The experiences of our participants, combined with evidence from other contact tracing studies from contexts beyond COVID-19, emphasize the importance of coordinated, multidimensional outreach and support of cases and contacts.

Lastly, our study raises concerns about the maintenance of volunteer-driven contact tracing programs, with particular regard to sustainability. Our study participants noted that the initial motivations to volunteer out of altruism and/or a desire for practical experience can wane over time, particularly when neighboring programs began hiring full-time contact tracers. We found that volunteer availability can also change over time, especially for students and those under-employed as a consequence of physical lockdowns. These factors can make it difficult to establish and maintain a stable workforce. Payment or other forms of reward have been shown to increase motivation and commitment of tracers in other settings [31, 35, 38, 51], and our participants echoed the importance of feeling valued and appreciated for their efforts. We recommend that programs unable to hire employees for contact tracing consider providing academic credit or certificates to volunteers to acknowledge their critical contributions to pandemic response.

A key strength of this study is its timeliness in providing insight into how to respond more effectively to an ongoing, global pandemic. This is the first qualitative evaluation we know of for COVID-19 contact tracing, despite the wealth of media attention devoted to this topic. Obtaining such direct feedback from key stakeholders in the COVID-19 crisis is critical for understanding the complexities of implementation. Second, the use of an established implementation framework adds strength and clarity to our findings and eases interpretability for broader contexts. Third, volunteer contact tracing is a feasible and adaptable solution to COVID-19 contact tracing, and this article provides several strategic recommendations specific to volunteer-driven programs that may increase effectiveness and efficiency. Fourth, the participants in this study were all experienced in health care or public health settings and as such were able to reflect deeply on their experiences and provide specific recommendations. Many of the recommended solutions to challenges were swiftly incorporated into practice by the Health Department, and future studies may evaluate the impact of these changes on contact tracing outcomes. Last, while video conferencing platforms are typically not used to conduct FGDs, this study demonstrates that this methodological approach is acceptable to participants and feasible, except for occasional reductions in audio quality. Those using this technology should provide written and verbal instructions to participants on best practices to optimize audio quality and maintain courtesy during the sessions.

There are several study limitations to note. First, participants' responses may have been influenced by group dynamics or social desirability bias. To partially compensate for this limitation, our analysis incorporated comments from a follow-up survey of participants soliciting additional comments that they might have felt uncomfortable sharing in a group setting, or simply forgotten to mention. Second, insights about barriers and facilitators of a volunteer-driven program may not apply to a professional-driven contact tracing program. Similarly, our experience with health sciences students may not be generalizable to other volunteer groups. However, several findings likely apply to other types of contact tracing programs, including strategies for reaching and engaging cases and contacts, the importance of adapting protocols and support systems to the needs of the local community, and the potential value in communication and coordination among different health agencies. Third, our findings include only the perspectives of volunteer tracers and not those of cases and contacts which will be explored in a subsequent analysis. Finally, while the insights and suggestions of the participants were used to modify the program, we unfortunately were not able evaluate their impact. With declining case numbers in Connecticut in June 2020, local health departments transitioned contact tracing responsibility to the state department of public health, and this program was discontinued.

The unique experiences of the FGD participants highlight several strategies for improving volunteer-driven COVID-19 contact tracing programs, including adopting flexible approaches to training and scheduling volunteers and fostering networks to facilitate support and learning among volunteers. While a largely volunteer-driven contact tracing program was feasible and acceptable in the context of a public health crisis, its greatest challenge was achieving sustainability after the initial case surge. Despite the difficulties of implementing COVID-19 contact tracing, our findings suggest that a workforce that is well-capacitated, networked with its surrounding organizations, and able to adapt its services to the unique needs of its clients can overcome many of these challenges.

3.6 References

1. Holshue ML, DeBolt C, Lindquist S, Lofy KH, Wiesman J, Bruce H, et al. First Case of 2019 Novel Coronavirus in the United States. N Engl J Med. 2020;382(10):929-36.
2. CDC. Coronavirus Disease 2019 (COVID-19): Cases, Data, and Surveillance. [Cited Feb 25, 2021] Available from: https://www.cdc.gov/coronavirus/2019-ncov/cases-updates/index.html
3. Otterman S. N.Y.C. Hired 3,000 Workers for Contact Tracing. It's Off to a Slow Start. . The New York Times. June 21, 2020. [Cited Feb 25, 2021] Available from: https://www.nytimes.com/2020/06/21/nyregion/nyc-contact-tracing.html
4. Jian SW, Cheng HY, Huang XT, Liu DP. Contact tracing with digital assistance in Taiwan's COVID-19 outbreak response. Int J Infect Dis. 2020;101:348-52.
5. Lauer SA, Grantz KH, Bi Q, Jones FK, Zheng Q, Meredith HR, et al. The Incubation Period of Coronavirus Disease 2019 (COVID-19) From Publicly Reported Confirmed Cases: Estimation and Application. Ann Intern Med. 2020;172(9):577-82.
6. Cheng HY, Jian SW, Liu DP, Ng TC, Huang WT, Lin HH, et al. Contact Tracing Assessment of COVID-19 Transmission Dynamics in Taiwan and Risk at Different Exposure Periods Before and After Symptom Onset. JAMA Intern Med. 2020;180(9):1156-1163.
7. Nishiura H, Linton NM, Akhmetzhanov AR. Serial interval of novel coronavirus (COVID-19) infections. Int J Infect Dis. 2020;93:284-6.
8. Liu Y, Eggo RM, Kucharski AJ. Secondary attack rate and superspreading events for SARS-CoV-2. Lancet. 2020;395(10227):e47.
9. Oran DP, Topol EJ. Prevalence of Asymptomatic SARS-CoV-2 Infection: A Narrative Review. Ann Intern Med. 2020;173(5):362-367.
10. Parron I, Alvarez J, Jane M, Cornejo Sanchez T, Razquin E, Guix S, et al. A foodborne norovirus outbreak in a nursing home and spread to staff and their household contacts. Epidemiol Infect. 2019;147:e225.
11. Hedican E, Miller B, Ziemer B, LeMaster P, Jawahir S, Leano F, et al. Salmonellosis outbreak due to chicken contact leading to a foodborne outbreak associated with infected delicatessen workers. Foodborne Pathog Dis. 2010;7(8):995-7.
12. Reddel S, Edmiston N. Contact tracing for STIs - new resources and supportive evidence. Aust Fam Physician. 2012;41(3):128-32.
13. Fox GJ, Barry SE, Britton WJ, Marks GB. Contact investigation for tuberculosis: a systematic review and meta-analysis. Eur Respir J. 2013;41(1):140-56.
14. Faye O, Boelle PY, Heleze E, Faye O, Loucoubar C, Magassouba N, et al. Chains of transmission and control of Ebola virus disease in Conakry, Guinea, in 2014: an observational study. Lancet Infect Dis. 2015;15(3):320-6.
15. Lokuge K, Caleo G, Greig J, Duncombe J, McWilliam N, Squire J, et al. Successful Control of Ebola Virus Disease: Analysis of Service Based Data from Rural Sierra Leone. PLoS Negl Trop Dis. 2016;10(3):e0004498.
16. Saurabh S, Prateek S. Role of contact tracing in containing the 2014 Ebola outbreak: a review. Afr Health Sci. 2017;17(1):225-36.
17. Hellewell J, Abbott S, Gimma A, Bosse NI, Jarvis CI, Russell TW, et al. Feasibility of controlling COVID-19 outbreaks by isolation of cases and contacts. Lancet Glob Health. 2020;8(4):e488-e96.

18. Ferretti L, Wymant C, Kendall M, Zhao L, Nurtay A, Abeler-Dorner L, et al. Quantifying SARS-CoV-2 transmission suggests epidemic control with digital contact tracing. Science. 2020;368(6491).
19. Braithwaite I, Callender T, Bullock M, Aldridge RW. Automated and partly automated contact tracing: a systematic review to inform the control of COVID-19. Lancet Digit Health. 2020;2(11):e607-e21.
20. Draper AD, Dempsey KE, Boyd RH, Childs EM, Black HM, Francis LA, et al. The first 2 months of COVID-19 contact tracing in the Northern Territory of Australia, March-April 2020. Commun Dis Intell (2018). 2020;44.
21. Glasgow RE, Harden SM, Gaglio B, Rabin B, Smith ML, Porter GC, et al. RE-AIM Planning and Evaluation Framework: Adapting to New Science and Practice With a 20-Year Review. Front Public Health. 2019;7:64.
22. Gaglio B, Shoup JA, Glasgow RE. The RE-AIM framework: a systematic review of use over time. Am J Public Health. 2013;103(6):e38-46.
23. Niccolai L, Shelby T, Weeks B, Schenck C, Goodwin J, Hennein R, et al. Community Trace: Rapid Establishment of a Volunteer Contact Tracing Program for COVID-19. Am J Public Health. 2021;111(1):54-7.
24. Memish ZA. Call to action for improved case definition and contact tracing for MERS-CoV. J Travel Med. 2019;26(5).
25. Centers for Disease Control and Prevention. Health Departments: Interim Guidance on Developing a COVID-19 Case Investigation & Contact Tracing Plan. U.S. Department of Health and Human Services, 2020. [Cited Feb 25, 2021] Available from: https://www.cdc.gov/coronavirus/2019-ncov/php/contact-tracing/contact-tracing-plan/overview.html
26. Guest G, Namey E, McKenna K. How Many Focus Groups Are Enough? Building an Evidence Base for Nonprobability Sample Sizes. Field Methods. 2016;29(1):3-22.
27. Miles MB, Huberman AM. Qualitative data analysis : an expanded sourcebook. 2nd ed. Thousand Oaks: Sage Publications; 1994.
28. Braun V, Clarke V. Thematic analysis. APA handbook of research methods in psychology, Vol 2: Research designs: Quantitative, qualitative, neuropsychological, and biological. APA handbooks in psychology®. Washington, DC, US: American Psychological Association; 2012. p. 57-71.
29. Lash RR, Donovan CV, Fleischauer AT, Moore ZS, Harris G, Hayes S, et al. COVID-19 Contact Tracing in Two Counties - North Carolina, June-July 2020. MMWR Morb Mortal Wkly Rep. 2020;69(38):1360-3.
30. Smith LE, Amlot R, Lambert H, Oliver I, Robin C, Yardley L, et al. Factors associated with adherence to self-isolation and lockdown measures in the UK: a cross-sectional survey. Public Health. 2020;187:41-52.
31. Ayakaka I, Ackerman S, Ggita JM, Kajubi P, Dowdy D, Haberer JE, et al. Identifying barriers to and facilitators of tuberculosis contact investigation in Kampala, Uganda: a behavioral approach. Implement Sci. 2017;12(1):33.
32. Fox GJ, Loan le P, Nhung NV, Loi NT, Sy DN, Britton WJ, et al. Barriers to adherence with tuberculosis contact investigation in six provinces of Vietnam: a nested case-control study. BMC Infect Dis. 2015;15:103.

33. Swanson KC, Altare C, Wesseh CS, Nyenswah T, Ahmed T, Eyal N, et al. Contact tracing performance during the Ebola epidemic in Liberia, 2014-2015. PLoS Negl Trop Dis. 2018;12(9):e0006762.
34. Faccini M, Cantoni S, Ciconali G, Filipponi MT, Mainardi G, Marino AF, et al. Tuberculosis-related stigma leading to an incomplete contact investigation in a low-incidence country. Epidemiol Infect. 2015;143(13):2841-8.
35. Ilesanmi OS. Learning from the challenges of Ebola Virus Disease contact tracers in Sierra Leone, February, 2015. Pan Afr Med J. 2015;22 Suppl 1:21.
36. Cochrane A, Collins P, Horwood JP. Barriers and opportunities for hepatitis B testing and contact tracing in a UK Somali population: a qualitative study. Eur J Public Health. 2016;26(3):389-95.
37. Guidelines for the investigation of contacts of persons with infectious tuberculosis. Recommendations from the National Tuberculosis Controllers Association and CDC. MMWR Recomm Rep. 2005;54(RR-15):1-47.
38. Tesfaye L, Lemu YK, Tareke KG, Chaka M, Feyissa GT. Exploration of barriers and facilitators to household contact tracing of index tuberculosis cases in Anlemo district, Hadiya zone, Southern Ethiopia: Qualitative study. PLoS One. 2020;15(5):e0233358.
39. Kaji A, Thi SS, Smith T, Charunwatthana P, Nosten FH. Challenges in tackling tuberculosis on the Thai-Myanmar border: findings from a qualitative study with health professionals. BMC Health Serv Res. 2015;15:464.
40. Figueroa-Munoz J, Palmer K, Poz MR, Blanc L, Bergstrom K, Raviglione M. The health workforce crisis in TB control: a report from high-burden countries. Hum Resour Health. 2005;3(1):2.
41. Danquah LO, Hasham N, MacFarlane M, Conteh FE, Momoh F, Tedesco AA, et al. Use of a mobile application for Ebola contact tracing and monitoring in northern Sierra Leone: a proof-of-concept study. BMC Infect Dis. 2019;19(1):810.
42. Shrestha A, Bhattarai D, Thapa B, Basel P, Wagle RR. Health care workers' knowledge, attitudes and practices on tuberculosis infection control, Nepal. BMC Infect Dis. 2017;17(1):724.
43. Tlale L, Frasso R, Kgosiesele O, Selemogo M, Mothei Q, Habte D, et al. Factors influencing health care workers' implementation of tuberculosis contact tracing in Kweneng, Botswana. Pan Afr Med J. 2016;24:229.
44. Koetter P, Pelton M, Gonzalo J, Du P, Exten C, Bogale K, et al. Implementation and Process of a COVID-19 Contact Tracing Initiative: Leveraging Health Professional Students to Extend the Workforce During a Pandemic. Am J Infect Control. 2020;48(12):1451-6.
45. Johns Hopkins University. COVID-19 Contact Tracing. Coursera 2020. [Cited Feb 25, 2021] Available from: https://www.coursera.org/learn/covid-19-contact-tracing
46. Markowski M, Bower H, Essex R, Yearley C. Peer learning and collaborative placement models in health care: a systematic review and qualitative synthesis of the literature. J Clin Nurs. 2021.
47. Marangu D, Mwaniki H, Nduku S, Maleche-Obimbo E, Jaoko W, Babigumira J, et al. Stakeholder perspectives for optimization of tuberculosis contact investigation in a high-burden setting. PLoS One. 2017;12(9):e0183749.

48. Duarte R, Neto M, Carvalho A, Barros H. Improving tuberculosis contact tracing: the role of evaluations in the home and workplace. Int J Tuberc Lung Dis. 2012;16(1):55-9.
49. Kigozi NG, Heunis JC, Engelbrecht MC. Yield of systematic household contact investigation for tuberculosis in a high-burden metropolitan district of South Africa. BMC Public Health. 2019;19(1):867.
50. Nyenswah T, Fallah M, Sieh S, Kollie K, Badio M, Gray A, et al. Controlling the last known cluster of Ebola virus disease - Liberia, January-February 2015. MMWR Morb Mortal Wkly Rep. 2015;64(18):500-4.
51. McMahon SA, Ho LS, Scott K, Brown H, Miller L, Ratnayake R, et al. "We and the nurses are now working with one voice": How community leaders and health committee members describe their role in Sierra Leone's Ebola response. BMC Health Serv Res. 2017;17(1):495.

3.7 Supplementary Information

Supplementary Text 3.1: Semi-structured focus group discussion guide

Intro

[Obtain verbal consent.]

Thank you for agreeing to participate in this study. Your experience working on the NHHD contact tracing program makes you an expert on this topic, and we would like to learn from you. This information will help the health department improve their contact tracing program and may also help other health departments by giving them advice about best ways to do contact tracing for COVID-19.

Domains

- Working in a volunteer program
    - **What made you decide to volunteer with this program?** (peer pressure, personal motivation)
    - **Tell me a little about what's it been like to work as a volunteer in this program.** (self-efficacy)
    - **What was it like for you in balancing this job with your other responsibilities?**
    - **How do you think this program in general, and your role in particular, evolved over time?**
    - **Recommendations?**

- Successes/Challenges
    - **What do you think went well in the calls you made?**
    - **What did you have difficulty with in those calls?**

- Training and Unexpected Experiences
    - **What is your opinion of the training you received?**
    - **What did you think of the Training Format and Content?**
    - **What were some of the unexpected experiences you encountered while doing the contact tracing/while volunteering with this program?**
    - **What tools or training do you wish you would have had?**
    - **What infrastructure or support do you wish the program had offered?**
    - **Recommendations?**

- Hopes and Concerns regarding the future
    - **How do you foresee the program changing over time?**
    - **How do you foresee your involvement in the program changing over time?**
    - **Recommendations?**

- **Is there anything else that you would like to add that we haven't talked about, but you think would be important for me to know?**

Thank you for your time!

Chapter Four. Antecedents to key contact tracing behaviors: A qualitative study drawing on interviews with COVID-19 cases and contacts

Tyler Shelby[1,2], Cailin Arechiga[2], Amanda J. Gupta, Rachel Hennein[1,2], Christopher Schenck[1], Brian E. Weeks[3,#a], Maritza Bond[3], Linda Niccolai[2], J. Lucian Davis[2,4,5], Lauretta E. Grau[2]

[1] Yale School of Medicine, New Haven, Connecticut, United States of America
[2] Department of Epidemiology of Microbial Diseases, Yale School of Public Health, New Haven, Connecticut, United States of America
[3] New Haven Health Department, New Haven, Connecticut, United States of America
[4] Pulmonary, Critical Care, and Sleep Medicine Section, Yale School of Medicine, New Haven, Connecticut, United States of America
[5] Center for Methods in Implementation and Prevention Science, Yale School of Public Health, New Haven, Connecticut, United States of America
[#a] Current Address: Norwalk Health Department, Norwalk, Connecticut, United States of America

This manuscript has been formatted for submission to AJPH as:

Tyler Shelby, Cailin Arechiga, Amanda J. Gupta, Rachel Hennein, Christopher Schenck, Brian E. Weeks, Maritza Bond, Linda Niccolai, J. Lucian Davis, Lauretta E. Grau. Antecedents to key contact tracing behaviors: A qualitative study drawing on interviews with COVID-19 cases and contacts.

4.1 Abstract:

Background: Low participation in contact tracing for COVID-19 dramatically reduces its impact, but little is known about how client experiences influence participation.

Methods: We invited consecutive COVID-19 cases and contacts reported to the New Haven Health Department for individual interviews about their contact tracing experiences. We analyzed transcripts thematically, organized themes using the Capability, Opportunity, Motivation, Behavior (COM-B) model, and identified candidate interventions using the linked Behavior Change Wheel Framework.

Results: We interviewed 21 cases and 12 contacts. Many felt physically or psychologically incapable of participating due to severe symptoms or uncertainty about contact tracing protocols. Structural factors and friends and family also influenced participation. Finally, physical and emotional state and low trust in and expectations of public health authorities reduced motivation to participate.

Conclusions: To improve participation in contact tracing, clients perceive the need for programs to respond to physical and emotional needs; increase clarity of public health communications; address structural and social factors that shape behaviors and opportunities of clients; and establish and maintain their trust. We identify multiple potential interventions that may help programs adopt these practices.

4.2 Background

Contact tracing, a non-pharmaceutical intervention used to limit transmission of a variety of infectious diseases (1, 2), has been widely adopted in response to the COVID-19 pandemic (3, 4), with demonstrated reductions in case incidence (5, 6) and mortality (7). However, contact tracing is challenging to implement because it depends on a chain of multiple, independent behaviors among cases and contacts: testing, answering of phone calls, reporting of exposed contacts, and isolating or quarantining when indicated. Cases and contacts may engage in some, all, or none of these, yet the overall impact of contact tracing relies on their cumulative completion rate (8). A recent evaluation of 14 U.S. COVID-19 contact tracing programs found low rates of interview completion among cases (including contact reporting) (9) below the benchmark of 60% proposed by the US Centers for Disease Control & Prevention (10), and additional studies outside the U.S. found rates of adherence to isolation and quarantine as low as 25% (11, 12).

Given the importance of contact tracing in the ongoing pandemic response, it is critical to identify and understand factors that influence participation. What is currently known about engagement in contact tracing is derived primarily from studies of other infectious diseases, digital contact tracing , or single steps of contact tracing such as self-isolation (13-17). Yet, many behavior change theories, models and frameworks exist that may help to classify elements influencing engagement throughout the COVID-19 contact tracing process and identify behavioral interventions to address them. The Capability, Opportunity, Motivation, Behavior (COM-B) model (18) is uniquely suited for this objective given its linkage to the Behavior Change Wheel (18) implementation framework, and has been used to identify and select behavior-modifying interventions in other contexts (19, 20). COM-B posits that there are three primary determinants (domains) of behavior: 1) Capability, 2) Opportunity, and 3) Motivation. These domains are divided into sub-domains capturing various elements that influence behavior. Capability includes Physical Capability (physical strengths or abilities) and Psychological Capability (prerequisite knowledge, mental skills/stamina); Opportunity includes Physical Opportunity (physical environment or resources) and Social Opportunity (social factors, norms, and relationships); and Motivation includes Reflective Motivation (intentional thought processes) and Automatic Motivation (impulses or emotions).

The goal of this study is to elicit from COVID-19 cases and contacts elements that may influence their participation and apply an implementation mapping approach using COM-B and the Behavior Change Wheel to identify potential interventions to promote engagement in contact tracing. We employed qualitative methods and thematic analysis to explore participant experiences and contextual elements shaping contact tracing behaviors.

4.3 Methods

Study Setting

This study was conducted as part of a multiple methods evaluation of the New Haven Health Department's (NHHD) emergency contact tracing program (21-23), which operated from March to June 2020 at the onset of the pandemic. This program was staffed primarily by university volunteers, including members of the study team.

Volunteers signed confidentiality agreements with the NHHD allowing them to assist with contact tracing and access limited client data necessary for their assigned tasks. New Haven, Connecticut is part of the New York Metropolitan Area and home to roughly 130,000 racially and ethnically diverse residents (44% White, 33% Black/African-American, 31% Hispanic/Latinx, and 5% Asian) (24). Between April and June 2020, the contact tracing program interviewed nearly 1,300 cases and notified nearly 1,100 contacts of their exposures.

Study Population Eligibility and Recruitment

We consecutively sampled cases and contacts (subsequently referred to as "clients") from the NHHD's contact tracing registry. Eligibility criteria included being (1) ≥18 years old, (2) a COVID-19 case or contact, and (3) interviewed by the NHHD's contact tracing program within the preceding 7–28 days. We set a target recruitment goal of 15 cases and 15 contacts based on estimates of the number of interviews needed to reach thematic saturation (25). Participants received a $20 gift card upon completing an interview. Enrollment continued until the NHHD's contact tracing program ended in June 2020.

Data Collection Procedures and Analysis

Basic demographic data (age, gender, race/ethnicity, and preferred language) were available for most interviewed clients, although race/ethnicity data were not available for contacts. We did not collect additional demographic information from study participants. Our semi-structured interview guide explored four topics: 1) experiences receiving tracing calls, 2) decisions about participating in the contact tracing interview, 3) behaviors and experiences related to testing, tracing, and isolating/quarantining, and 4) participant recommendations to improve the contact tracing program. The interview focused on the four behaviors thought to be essential to successful contact tracing: (testing, answering phone calls, participating in contact tracing interviews, and adhering to isolation or quarantine, as displayed in Supplementary Figure 4.1)

The interview team included a male MD/PhD student (TS) and a female, Spanish-speaking MPH student CA) who were trained in qualitative interviewing. They telephoned clients up to three times over a one-week period to invite them to participate in the study and left voice messages with callback numbers if clients did not answer. Interviews were conducted via telephone, audio-recorded, and subsequently transcribed verbatim (and translated to English, if applicable) using an automated service (Trint, London, United Kingdom). Transcripts were proofread against the recordings and corrected as needed. Participants did not review the data or study findings. TS and LG iteratively assessed the content of interviews for saturation until no new themes emerged.

The coding team (TS and LG) adapted a codebook from a prior qualitative evaluation of contact tracing (23) and added new codes as needed. They independently coded all transcripts and met to resolve any coding discrepancies. They then entered the coded transcripts into ATLAS.ti (Version 8, Berlin, Germany) for analysis.

TS, LD, and LG analyzed the coded data (26) to identify preliminary themes, and subsequently narrowed the analytic scope to the four client behaviors of interest. They classified themes and supporting quotes as barriers to or facilitators of participation in contact tracing and organized them within all relevant COM-B domains (18).

Human Subjects and Consent Procedures

The study protocol was approved by the Yale Human Subjects Committee. We collected verbal consent at the start of each phone interview, prior to audio-recording.

4.4 Results

Study Sample Characteristics

Between May 25 and July 9, 2020, we called 64 cases and 83 contacts of whom 35 cases and 38 contacts answered or called back, and 21 cases and 12 contacts agreed to participate. Three contacts had tested positive for COVID-19 by the time of the study interview. Participants' median age was 41, 61% were female, and the largest racial/ethnic group in our sample was Hispanic/Latinx (48%) (Table 4.1), which is roughly representative of the source population (22).

Table 4.1: Participant Characteristics

Characteristics (n=33)	**n (%)**[a]
Participant Type	
Case	21 (64)
Contact	9 (27)
Contact who subsequently tested positive	3 (9)
Age, median years (Q1, Q3)[b]	40 (32, 52)
Gender	
Female	20 (61)
Male	13 (39)
Race/Ethnicity	
Non-Hispanic White	5 (15)
Black/African American	4 (12)
Hispanic/Latinx	16 (48)
Asian	2 (6)
Native American	1 (3)
Unknown	5 (15)
Language Spoken	
English	21 (64)
Spanish	12 (36)

Legend

[a] *Unless otherwise specified*

[b] *Q1, quartile 1; Q3, quartile 3*

Themes, Facilitators and Barriers

We identified seven themes that cut across the four behaviors and three COM-B domains (Table 4.2). While the themes were broadly similar across case and contact groups, we note relevant differences below when applicable, summarize the individual themes within each COM-B domain, and present supporting quotes in Table 4.3.

Table 4.2: Facilitators and barriers mapped onto behaviors, themes, and COM-B components (Capability, Opportunity, Motivation)

Themes		Testing	Answering	Participating in Interview	Isolation/Quarantine
Capability					
Symptom Severity	B	-	Symptoms limit ability to answer	Symptoms limit ability to speak	Symptoms increase difficulty
	F	-	-	-	-
Essential Knowledge	B	Lacking awareness of where/when to get tested limits uptake	Cases/contacts are surprised by call due to being unaware of tracing	Lacking understanding of tracing limits participation	Lacking understanding of I/Q protocols increases confusion
	F	-	-	Education increases participation	-
Opportunity					
Structural Context	B	Lacking insurance or transportation impedes care seeking and testing	English-only outreach limits receptiveness	English-only outreach impedes communication; Work/home responsibilities limit availability	Lacking food or secure/spacious housing and need for work limit feasibility
	F	In-home testing and policies increase uptake	-	Having staff who are able to speak the patient's preferred language increases receptiveness	Organizational support, paid work leave, and spacious housing increase feasibility
Interpersonal Ties	B	-	Cases block outreach to contacts when they do report all contacts	-	Caregiving responsibilities make complete adherence not feasible
	F	Prompting by family/peers increases uptake	Cases alert contacts to incoming calls; Family assistance of ill cases increases feasibility	Family assistance of ill cases increases feasibility; Shared experiences reduce fears	Encouragement increases adherence; Proving food, housing, financial support increases feasibility.
Motivation					
Symptom Severity	B	-	-	-	Lack of symptoms reduces motivation
	F	Symptoms increase motivation	-	-	Symptoms increase motivation
Anticipated Outcomes	B	Belief that testing will not lead to support, assumed infection status, and desire to exit quarantine quickly limit uptake	Belief that answering will not lead to support limits uptake	-	-
	F	Curiosity and desire to ensure medical care increases uptake;	Desire for information increases uptake	Desires for information, for medical/resource support, and to protect community increase uptake	Desires to protect community increase uptake
Trust in Authority	B	-	-	Potential for data misuse and disorganized outreach lead to fear and loss of credibility	-
	F	Trust in guidance increases uptake	Use of Caller ID limits concerns about scam callers	Caller's advance knowledge of client birth date increases trust	Trust in guidance increases adherence

Emotional Responses	B	-	-	Shock/anxiety/anticipated stigma impede interviews; Disorganized outreach leads to frustration	Boredom and loneliness negatively impact mental health
	F	-	-	Contributing to public health is gratifying; Communication skills address negative emotions	Coping strategies improve mental health; Follow-up calls provide reassurance during I/Q

Abbreviations:
COM-B: Capability, Opportunity, Motivation, Behavior
B: Barrier
F: Facilitator
I/Q: Isolation and quarantine

Table 4.3: Supporting quotes within each theme and COM-B domain

COM-B Domain	**Theme**	**Quote**
Capability	Symptom Severity	I had a lot of cough and I couldn't speak…my wife just put [the tracer] on speaker and [I was] listening to [them] and she was answering for me. (Participant 10, Case)
		I [isolated] almost three weeks 'cause I was weak and my taste buds hadn't quite got back yet…. I lost eight pounds and I was already thin… That was the hardest part. (Participant 2, Case)
	Essential Knowledge	I was surprised [to receive the call]. I didn't expect that call at all…I didn't know [contact tracing] was a thing. (Participant 4, Contact)
		At first, I didn't want to give the names [of my contacts], but then when they explained to me the reason why [it] was important to them… I answered the questions. (Participant 3, Contact who tested positive)
		[I asked the tracers,] do I need two negative tests to stop self-isolation? And the [city's tracers] said, yes, you should get retested and [the university] said they were not recommending retests. (Participant 12, Case)
Opportunity	Structural Context	I answered [the contact tracing call] and I said [I was busy and] that they could call back in an hour. They never did. (Participant 24, Contact)
		[My employers] are not supporting me or paying me either. Because I'm not working. They pay you when you work. (Participant 28, Case)
		The last week before I was better, I had to put a mask on and run to the closest store…because we had been running out of food. (Participant 16, Contact who tested COVID-positive)
		I brought [my employers] documentation from the clinic…they paid me for not going to work for two weeks…The clinic was [also] helping me with food, that they give once a month. (Participant 7, Case)
		English for me is the second language. Sometimes you have words or little bits [that are difficult] to understand exactly what the person is talking about. (Participant 15, Contact)
		It was hard to find a doctor… My family is not registered in any clinic. (Participant 25, Contact who tested positive)
	Interpersonal Ties	I started having symptoms again and my wife is also a nurse in my country…she said it was necessary to do the COVID test. (Participant 10, Case)
		I told [my contacts about my positive test] …and then I told them they would probably be receiving a call [from the health department]. (Participant 12, Case)
		Then [a friend with COVID-19] asked if [the NHHD] called me and I said yes, it's no big deal. (Participant 27, Case)

		I didn't exactly give names and phone numbers, but I just said that it was my family… I [also] didn't completely isolate myself because I have my kids. I was being very careful, right? But I cooked (Participant 7, Case)
Motivation	Symptom Severity	I went to the hospital the day after [symptom onset] to get the test… (Participant 9, Case)
	Anticipated Outcomes	The reason I requested a test was because I wanted to make sure I would get adequate health care. I have ulcerative colitis. (Participant 13, Case)
		What [my family] did was they went by my tests and figured they had the same thing 'cause we were all together that Sunday [before I was diagnosed]. (Participant 2, Case)
		My mom wasn't happy with [the contact tracing calls which she didn't answer]…she felt that a phone call wasn't going to help her. She needed an actual doctor. (Participant 25, Contact who tested positive)
	Trust in Authority	[My wife, a case,] was a little intimidated because, although it was explained how the information would be used, a potential fear she had was the information being manipulated somehow in terms of her personal life. (Participant 4, Contact)
		When the phone rang, the number of the person and the name of the [health department] come on my tv screen. So I knew it wasn't a scam….after [the tracer] hung up, I knew exactly what I had to do. I called my doctor and I told him. [He] put me on course, set me up with an appointment to get tested again. (Participant 17, Contact)
	Emotional Responses	I have anxiety. I got overwhelmed. And I was like, "I can't do [the interview]." …I [first] felt the support, but then it became annoying because they [were] calling me almost every day. (Participant 19, Case)
		It was almost like getting a phone call telling me I had AIDS… So everything for me is going to be like, you can't do this, you can't do that… So it was almost to the point where I could have cried when they told me because it was how people [were reacting] to it.. (Participant 2, Case)
		You get up in the morning and you look around, you go back and you wash. You try to make yourself a little something to eat. You open up the door and look out. You don't go out the door. You just look out the door. You close the door and you walk around your apartment again and you're saying, "what in the heck am I going to do today?" …On my second week of [quarantine], I said I know I have a backyard. I have some seeds. I'm gonna make myself a little small garden in my backyard. (Participant 17, Contact)

Capability Domain

We identified two themes, *Symptom Severity* and *Essential Knowledge*, related to clients' capacity to participate in contact tracing. *Symptom Severity* describes how COVID-19 symptoms influenced clients' *Physical Capability*. *Essential Knowledge* describes how knowledge about the purpose of and procedures for testing and tracing influenced clients' *Psychological Capability*.

Symptom Severity Theme

Several participants described how symptoms made it difficult or infeasible to answer phone calls or speak to contact tracers. One case was hospitalized at the time of the contact tracing call, and his daughter spoke on his behalf. Other participants noted that moderate or severe symptoms also made isolation especially difficult.

Essential Knowledge Theme

Limited awareness of COVID-19 symptoms, testing locations, or contact tracing procedures acted as a barrier to contact tracing engagement for several participants. For example, not knowing how personal data would be used or protected caused some cases to be wary of fully engaging with the interview, although some contact tracers successfully addressed these concerns. Other participants were confused by quarantine and isolation instructions, and receiving conflicting information from different contact tracing programs caused further confusion.

Opportunity Domain

We identified two themes, *Structural Context* and *Interpersonal Ties*, related to clients' possibility of participating in contact tracing. *Structural Context* describes how structural factors (fixed economic, social, and policy factors) influenced *Physical* and *Social Opportunity* to participate in contact tracing. *Interpersonal Ties* describes ways in which social roles and connections with family, friends, or colleagues further influenced clients' *Social Opportunity*.

Structural Context Theme

Lacking transportation or home-testing services or receiving tracing calls at inconvenient times hindered client engagement. Participants also cited concerns about loss of income, housing stability, and food insecurity as barriers to isolation/quarantine. The difficulty of isolation and quarantine was increased in homes with inadequate space to allow household members to effectively separate from one another. Occasionally, organizations and employers sought to counteract these barriers. Several participants received food from clinics and volunteer organizations. Some employers paid cases during isolation. A systems-level facilitator was policy-mandated testing, requiring some participants to test in order to enter health care clinics or travel.

Social Opportunity for engagement was influenced by access to medical providers and language services. Those lacking health insurance or established relationships with care providers experienced difficulties seeking care during isolation/quarantine. For participants whose preferred language was not English, language barriers made answering calls and participating in interviews infeasible or challenging, although some noted that multilingual outreach workers or translation services enabled successful interaction with the program.

Interpersonal Ties Theme

Participants often described how relationships with family or friends could promote testing and tracing behaviors and reassure participants about the contact tracing experience. Peers frequently encouraged engagement in testing or tracing, some cases even alerting their contacts to expect tracing calls. As previously noted, family members often helped by answering phone calls for symptomatic cases and caring for those in isolation or quarantine. Interpersonal ties could also hinder contact tracing efforts. Some cases did not provide tracers with information about their contacts (names and phone numbers), thereby preventing any outreach from the health department to them. Caregiving responsibilities in the home (e.g., caring for children) posed additional barriers to adhering to isolation/quarantine guidelines.

Motivation Domain

We identified some aspects of *Symptom Severity* and three additional themes, *Anticipated Outcomes*, *Trust in Authority*, and *Emotional Responses*, that related to clients' motivation to participate in contact tracing. *Symptom Severity* describes ways in which symptoms, or lack thereof, influenced clients' *Reflective Motivation*. *Anticipated Outcomes* describes ways in which clients' beliefs in the consequences of participation, whether positive, negative, or neutral, also influenced *Reflective Motivation*. *Trust in*

Authority is the last theme associated with *Reflective Motivation*, and it describes the influence of clients' trust in providers and health systems. Finally, *Emotional Responses* describes ways in which clients' emotions influenced their *Automatic Motivation*.

Symptom Severity Theme

Participants frequently described how symptoms prompted testing or isolation. By contrast, one contact without any symptoms described the quarantine experience as "so abstract" that lack of symptoms made it "hard to keep telling myself this is real."

Anticipated Outcomes Themes

Participants varied in their expectations regarding consequences of engagement with contact tracing. Most tested or answered phone calls to ensure that they received adequate social or medical support, even when asymptomatic. However, one participant tested out of curiosity, and others assumed their status was positive based on known exposures and chose not to test. Several participants cited wanting to prevent transmission to others as their reason for participating in testing and tracing. By contrast, lacking belief in benefits of testing, or anticipating potential negative outcomes (e.g., mandatory isolation) reduced the likelihood of engagement.

Trust in Authority Theme

A commonly cited motivation to engage in the four behaviors was trust in the health system and guidelines. Fears about misuse of data or mishandling of medical care were common barriers to engagement. Occasional disorganization in outreach efforts also diminished program credibility and led to client frustration and mistrust. Several strategies (e.g., tracer being able to confirm a case's date of birth, using Caller IDs) counteracted these tendencies and may have increased motivation to engage in the contact tracing behaviors. Participants also mentioned their pre-established relationships with medical providers as reasons for engaging in testing or tracing behaviors.

Emotional Responses Theme

Many participants described feeling shocked or anxious upon receiving a positive test result or exposure notification, and others anticipated being stigmatized by others. These emotions could distract participants during the contact tracing call, but tracers who communicated clearly and empathically helped some remain calm. Others found the calls frustrating, particularly when they were numerous, duplicative or disorganized. One participant described ending a call prematurely for this reason. Other common emotional responses included boredom or loneliness during isolation/quarantine. Coping strategies such as communicating electronically with family and friends and staying physically active mitigated such feelings and made isolation/quarantine more tolerable.

4.5 Discussion

As the pandemic continues to evolve, contact tracing may continue to contribute towards reductions in transmission and mortality and provide opportunities for resource provision and improved understanding of transmission patterns. This is one of the first studies to qualitatively examine the experiences of COVID-19 cases and contacts with contact tracing, and its findings may help to understand and address elements influencing participation in testing, answering phone calls, interviews, and isolation/quarantine. Below, we situate our findings within the existing contact tracing literature, and apply the Behavior Change Wheel to select intervention functions targeted to the facilitators/barriers that we identified in this study, with the ultimate goal of increasing client engagement with COVID-19 contact tracing (Table 4.4). As there is evidence that tailored interventions are effective in addressing determinants of practice, we propose several potential intervention components that may be evaluated in the future for their effectiveness in promoting participation in contact tracing.

Table 4.4: Potential interventions and intervention functions within each COM-B Component and Theme

COM-B Components	Themes	Intervention Functions	Potential Intervention Activities	Behaviors
Capability	Symptom Severity	Enablement	Provide additional means of outreach and data collection (SMS, email, web application) for those with moderate-severe illness	A, P
			Monitor symptoms during Isolation and Quarantine and provide direct linkages to medical care	I/Q
	Essential Knowledge	Education	Increase community awareness of testing locations and COVID-19 symptoms	T
			Directly educate cases at time-of-testing that they will receive a contact tracing call	A
			Broadly educate the community that exposed contacts will receive a contact tracing call	A
			Educate clients (at testing sites and at the onset of contact tracing interviews) about the importance of contact tracing and how data will be protected	P
			Provide clear isolation and quarantine instructions	I/Q
Opportunity	Structural Context	Enablement	Provide transportation for testing	T
			Make testing free for those without health insurance, and advertise its availability	T
			Hire contact tracers fluent in common non-English languages and have interpreter services available	A, P
			Offer paid work leave	A, P, I/Q
		Training	Train contact tracers to screen for and identify resource needs and provide linkages to local resources	I/Q
	Interpersonal Ties	Modeling	Encourage and equip community members to promote engagement amongst peer groups	T, A, P, I/Q
			Encourage cases to inform their contacts that they will receive a contact tracing call, and provide suggestions about how to break the news	A, P
			Recruit community role models	T, A, P, I/Q
		Enablement	Establish a family point-of-contact to facilitate outreach when case is unavailable or unable to participate in the interview	A, P
			Help clients identify supporters in their social networks who may facilitate support them and give advice on how to break the news and seek help.	I/Q
Motivation	Symptom Severity	Persuasion	Emphasize potential harms of breaking isolation or quarantine among asymptomatic clients	I/Q
	Anticipated Outcomes	Incentivization	Screen for social and medical support needs, link clients to services, and advertise available resources.	T, A, P
		Persuasion	Emphasize the benefits to family and/or community of participating fully in contact tracing	T, A, P, I/Q
	Trust in Authority	Persuasion	Establish community trust in health systems and reduce fears regarding misuse of data via community messaging and peer- and provider-driven outreach	T, A, P, I/Q
	Emotional Response	Enablement	Allow clients to select the frequency and mode of communication to avoid intrusion	A, P, I/Q
		Persuasion	Use messages that emphasize the positive role one can play in protecting their community	P, I/Q
		Training	Equip contact tracers with skills to respond appropriately to client emotions during interview	P
		Enablement	Advertise and provide access to hotlines, communication forums, home-based activities	I/Q

Abbreviations
COM-B: Capability, Opportunity, Motivation, Behavior
T: Testing
A: Answering phone calls
P: Participating in interviews
I/Q: Isolation and quarantine

Our findings suggest that symptom severity and baseline knowledge influenced participants' Capability to engage in contact tracing. This is consistent with other studies highlighting the importance of community awareness and education in achieving engagement with COVID-19 health guidance and tuberculosis contact tracing (13, 27). However, symptoms may influence contact tracing engagement in unique ways in the COVID-19 context, given the reliance on timeliness of tracing and propensity for symptoms to prevent engagement. This contrasts with contact tracing for STIs or TB in which pathogen transmission dynamics and end-goals of tracing differ, permitting more time to conduct contact tracing . Several potential intervention activities can address these elements. Alternative modes of data collection, such as SMS communications or web-app surveys implemented in several U.S. states (28), could enable better access to those with moderate-to-severe symptoms. To increase uptake of testing, programs could also expand community-wide education about when and where to test. When getting tested, individuals could be informed to expect and answer contact tracing calls should they test positive and be assured about data privacy and confidentiality concerns. Clear and standardized instructions on the duration and rules for isolation and quarantine might also improve adherence and reduce confusion, although continually evolving guidelines make this goal challenging. Given the difficulty clients report understanding and retaining this information, especially when receiving potentially upsetting news about a COVID-19 diagnosis or exposure, printed or electronic informational booklets could be provided at the time of testing or client interview.

Our data also suggest that environment and social ties strongly influenced Opportunity to participate in contact tracing. Consistent with the previous literature (13-15, 29), participants noted how access to medical care and support resources and social vulnerability influenced contact tracing behaviors. The data suggest ways to promote contact tracing behaviors could include providing transportation to testing sites, offering home-testing, hiring multilingual contact tracers, offering paid work leave, supporting caregiving or urgent errand needs, and delivering care packages of food, masks, and cleaning supplies. Previous studies drawing on focus groups with COVID-19 contact tracers or with the general population support these strategies (23, 27). Our qualitative analyses suggested that having cases notify contacts about what to expect from a contact tracing call and helping contacts identify peer resources to support isolation and quarantine can all be valuable. Communication between cases and contacts is often encouraged or relied upon in contact tracing for other communicable diseases (30) and may partially explain the previously observed correlations between success rates of contact outreach within case-contact clusters (22). In contrast, social norms in some communities may reinforce a lack of adherence to COVID-19 health guidance (11, 29).

Last, our analysis suggested that symptom severity, anticipated outcomes, trust in health authorities, and emotions could influence client Motivation to participate in contact tracing. Recent studies also emphasize that anticipated benefits of participation (15, 16, 29, 31) and trust in authority are important predictors of adherence to public health interventions (32, 33). Building and maintaining such trust can be positively influenced by more transparent communications and better patient-provider relationships (34) and negatively influenced by misinformation (35) and privacy concerns (34). We also found that initiating tracing through known healthcare professionals or using verifiable Caller ID, and addressing privacy concerns reinforced credibility and build trust, while redundant or uncoordinated efforts did the opposite. Other potential interventions to increase trust in contact tracing indirectly supported by our analysis include hiring community members as contact tracers or peer educators and role models. We also observed that emotions affected motivation, including fear and anticipated stigma, as described with tuberculosis contact tracing (13). Our analysis also suggests that equipping tracers with good communication skills is important. Training tracers to address shock or anxiety may help clients remain engaged when receiving test results or exposure notifications, and knowing how to elicit and address client needs is critical to success. Other interventions, stemming indirectly from the study findings, include connecting clients to mental health hotlines or online communication forums. Helping them remain active at home may decrease the loneliness and boredom associated with isolation and quarantine. Furthermore, better coordinating outreach efforts and allowing clients choices in the method and frequency of contact may enhance motivation to engage in contact tracing.

Using COM-B in this study enhanced the utility of our findings by connecting the identified barriers and facilitators and possible interventions to the Behavior Change Wheel (18). Some of the potential mechanisms for influencing change are shown for the 25 interventions proposed in Table 4, including 1) Enablement (i.e., increasing means of engagement or reducing barriers) 2) Education (i.e., increasing knowledge, 3) Persuasion, (i.e., using communication to create positive or negative feelings), 4) Modeling, (i.e., providing an example of desired behavior), 5) Training, (i.e., imparting new skills), and 6) Incentivization, (i.e., establishing an expectation of reward). Future implementation and evaluation of these interventions these activities should consider feasibility and acceptability of each function based on local context and resources.

Limitations and Strengths

There are several limitations to this study. First, poor recall of contact tracing over time may have introduced some inaccuracies in the data, though we sought to minimize this by interviewing clients soon after their original contact tracing call. Second, social desirability bias may have influenced participants to present themselves in positive terms, although interviewers were trained to be non-judgmental towards and supportive of participants to minimize this possibility. Third, although data saturation was achieved, participants were recruited from a single contact tracing program and no data were available from clients who were not reached by or declined to participate with the program, likely limiting the transferability of our findings to different populations or settings.

A strength of this study is its use of qualitative data collected at the onset of the COVID-19 pandemic. While many contact tracing evaluations have described quantitative outcomes, there are few reports describing reasons for loss of engagement and fewer that individually engage clients. Eliciting participant experiences, expressed in their own words, yielded new insights into the complexities of increasing contact tracing uptake.

Another strength is the inclusion of both cases and contacts, as well as both English and Spanish speakers. A final strength is the use of the COM-B model to frame the analysis and findings. This structuring allowed us to link our identified themes with relevant COM-B domains and link suggested intervention activities with their core functions.

Conclusion

This study is among the first to seek to understand, from the perspective of COVID-19 cases and contacts, how their environments, experiences, and perceptions may shape contact tracing behaviors. Within the COM-B framework, Capability was shaped by symptom severity and COVID-19-relevant knowledge, Opportunity was shaped by structural, environmental, and social factors, and Motivation was shaped by symptoms, anticipated consequences of engagement, trust, and emotional responses. Tracing strategies may benefit from accounting for and addressing the many environmental- and client-level elements identified herein, and clients' symptoms and peer interactions may be more influential in the setting of COVID-19 contact tracing compared to other disease contexts.

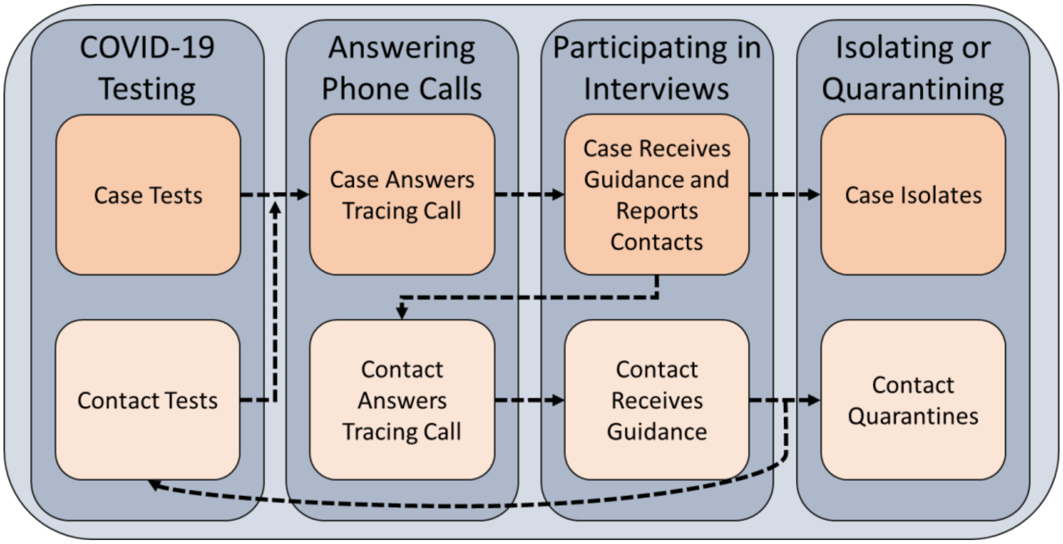
4.6 References

1. Fox GJ, Barry SE, Britton WJ, Marks GB. Contact investigation for tuberculosis: a systematic review and meta-analysis. Eur Respir J. 2013;41(1):140-56.
2. Ooi PL, Lim S, Chew SK. Use of quarantine in the control of SARS in Singapore. Am J Infect Control. 2005;33(5):252-7.
3. Jian SW, Cheng HY, Huang XT, Liu DP. Contact tracing with digital assistance in Taiwan's COVID-19 outbreak response. Int J Infect Dis. 2020;101:348-52.
4. Lee SW, Yuh WT, Yang JM, Cho YS, Yoo IK, Koh HY, et al. Nationwide Results of COVID-19 Contact Tracing in South Korea: Individual Participant Data From an Epidemiological Survey. JMIR Med Inform. 2020;8(8):e20992.
5. Fetzer T, Graeber T. Does Contact Tracing Work? Quasi-Experimental Evidence from an Excel Error in England. Working Paper No. 521. 2020.
6. Girum T, Lentiro K, Geremew M, Migora B, Shewamare S. Global strategies and effectiveness for COVID-19 prevention through contact tracing, screening, quarantine, and isolation: a systematic review. Trop Med Health. 2020;48(1):91.
7. Yalaman A, Basbug G, Elgin C, Galvani AP. Cross-country evidence on the association between contact tracing and COVID-19 case fatality rates. Sci Rep. 2021;11(1):2145.
8. Davis EL, Lucas TCD, Borlase A, Pollington TM, Abbott S, Ayabina D, et al. Contact tracing is an imperfect tool for controlling COVID-19 transmission and relies on population adherence. Nature Communications. 2021;12(1):5412.
9. Lash RR, Moonan PK, Byers BL, Bonacci RA, Bonner KE, Donahue M, et al. COVID-19 Case Investigation and Contact Tracing in the US, 2020. JAMA Network Open. 2021;4(6):e2115850-e.
10. Prioritizing COVID-19 Contact Tracing Mathematical Modeling Methods and Findings 2020 [March 29, 2021]. Available from: https://www.cdc.gov/coronavirus/2019-ncov/php/contact-tracing/contact-tracing-plan/prioritization/mathematicalmodeling.html.
11. Smith LE, Amlot R, Lambert H, Oliver I, Robin C, Yardley L, et al. Factors associated with adherence to self-isolation and lockdown measures in the UK: a cross-sectional survey. Public Health. 2020;187:41-52.
12. Steens A, Freiesleben de Blasio B, Veneti L, Gimma A, Edmunds WJ, Van Zandvoort K, et al. Poor self-reported adherence to COVID-19-related quarantine/isolation requests, Norway, April to July 2020. Euro Surveill. 2020;25(37).
13. Ayakaka I, Ackerman S, Ggita JM, Kajubi P, Dowdy D, Haberer JE, et al. Identifying barriers to and facilitators of tuberculosis contact investigation in Kampala, Uganda: a behavioral approach. Implement Sci. 2017;12(1):33.
14. Tesfaye L, Lemu YK, Tareke KG, Chaka M, Feyissa GT. Exploration of barriers and facilitators to household contact tracing of index tuberculosis cases in Anlemo district, Hadiya zone, Southern Ethiopia: Qualitative study. PLoS One. 2020;15(5):e0233358.
15. Megnin-Viggars O, Carter P, Melendez-Torres GJ, Weston D, Rubin GJ. Facilitators and barriers to engagement with contact tracing during infectious disease outbreaks: A rapid review of the evidence. PLoS One. 2020;15(10):e0241473.

16. Heffner J, Vives ML, FeldmanHall O. Emotional responses to prosocial messages increase willingness to self-isolate during the COVID-19 pandemic. Pers Individ Dif. 2021;170:110420.
17. Shelby T, Caruthers T, Kanner OY, Schneider R, Lipnickas D, Grau LE, et al. Pilot Evaluations of Two Bluetooth Contact Tracing Approaches on a University Campus: Mixed Methods Study. JMIR Form Res. 2021;5(10):e31086.
18. Michie S, van Stralen MM, West R. The behaviour change wheel: a new method for characterising and designing behaviour change interventions. Implement Sci. 2011;6:42-.
19. Arden MA, Hutchings M, Whelan P, Drabble SJ, Beever D, Bradley JM, et al. Development of an intervention to increase adherence to nebuliser treatment in adults with cystic fibrosis: CFHealthHub. Pilot Feasibility Stud. 2021;7(1):1.
20. Bonner C, Jansen J, McKinn S, Irwig L, Doust J, Glasziou P, et al. General practitioners' use of different cardiovascular risk assessment strategies: a qualitative study. Med J Aust. 2013;199(7):485-9.
21. Niccolai L, Shelby T, Weeks B, Schenck C, Goodwin J, Hennein R, et al. Community Trace: Rapid Establishment of a Volunteer Contact Tracing Program for COVID-19. Am J Public Health. 2020:e1-e4.
22. Shelby T, Schenck C, Weeks B, Goodwin J, Hennein R, Zhou X, et al. Lessons Learned From COVID-19 Contact Tracing During a Public Health Emergency: A Prospective Implementation Study. Frontiers in Public Health. 2021;9(1196).
23. Shelby T, Hennein R, Schenck C, Clark K, Meyer AJ, Goodwin J, et al. Implementation of a volunteer contact tracing program for COVID-19 in the United States: A qualitative focus group study. PLOS ONE. 2021;16(5):e0251033.
24. QuickFacts: New Haven City, Connecticut. Unites States Census Bureau.
25. Guest G, Bunce A, Johnson L. How Many Interviews Are Enough?:An Experiment with Data Saturation and Variability. Field Methods. 2006;18(1):59-82.
26. Braun V, Clarke V. Thematic analysis. APA handbook of research methods in psychology, Vol 2: Research designs: Quantitative, qualitative, neuropsychological, and biological. APA handbooks in psychology®. Washington, DC, US: American Psychological Association; 2012. p. 57-71.
27. Benham JL, Lang R, Kovacs Burns K, MacKean G, Leveille T, McCormack B, et al. Attitudes, current behaviours and barriers to public health measures that reduce COVID-19 transmission: A qualitative study to inform public health messaging. PLoS One. 2021;16(2):e0246941.
28. Oklahoma Contact Tracing now Includes Text Messages [7/19/2021]. Available from: https://oklahoma.gov/covid19/newsroom/2020/july/oklahoma-contact-tracing-now-includes-text-messages-07242020.html.
29. Coroiu A, Moran C, Campbell T, Geller AC. Barriers and facilitators of adherence to social distancing recommendations during COVID-19 among a large international sample of adults. PLoS One. 2020;15(10):e0239795.
30. Centers for Disease C, Prevention. Recommendations for partner services programs for HIV infection, syphilis, gonorrhea, and chlamydial infection. MMWR Recomm Rep. 2008;57(RR-9):1-83; quiz CE1-4.
31. Miyajima T, Murakami F. Self-Interested Framed and Prosocially Framed Messaging Can Equally Promote COVID-19 Prevention Intention: A Replication and

Extension of Jordan et al.'s Study (2020) in the Japanese Context. Front Psychol. 2021;12:605059.
32. Pak A, McBryde E, Adegboye OA. Does High Public Trust Amplify Compliance with Stringent COVID-19 Government Health Guidelines? A Multi-country Analysis Using Data from 102,627 Individuals. Risk Manag Healthc Policy. 2021;14:293-302.
33. Figueiras MJ, Ghorayeb J, Coutinho MVC, Marôco J, Thomas J. Levels of Trust in Information Sources as a Predictor of Protective Health Behaviors During COVID-19 Pandemic: A UAE Cross-Sectional Study. Frontiers in Psychology. 2021;12(2780).
34. Doty AMB, Powell RE, Carr BG, Nelson DB, Rising KL. Identification of Approaches to Improve Patient Trust in Health Systems: A Group Concept Mapping Study. J Healthc Manag. 2018;63(5):e116-e29.
35. Naeem SB, Bhatti R, Khan A. An exploration of how fake news is taking over social media and putting public health at risk. Health Info Libr J. 2021;38(2):143-9.

4.7 Supplementary Information



Supplementary Figure 4.1. Conceptual model of key contact tracing behaviors.

Chapter Five. Pilot Evaluations of Two Bluetooth Contact Tracing Approaches on a University Campus: A Mixed Methods Study

Tyler Shelby[1,2], Tyler Caruthers[1], Oren Y Kanner[3], Rebecca Schneider[3], Dana Lipnickas[3], Lauretta E Grau[1], Rajit Manohar[4], Linda Niccolai[1]

1. Yale School of Public Health, Department of Epidemiology of Microbial Diseases, New Haven, Connecticut, USA
2. Yale School of Medicine, New Haven, Connecticut, USA
3. Yale University Information and Technology Services, New Haven, Connecticut, USA
4. Yale School of Engineering and Applied Science, New Haven, Connecticut, USA

This manuscript has been previously published as:

Shelby T, Caruthers T, Kanner OY, Schneider R, Lipnickas D, Grau LE, Manohar R, Niccolai L. Pilot Evaluations of Two Bluetooth Contact Tracing Approaches on a University Campus: A Mixed Methods Study, JMIR Formative Research, 2021; 5(10):e31086

5.1 Abstract

Background: Many have proposed the use of Bluetooth technology to help scale-up contact tracing for COVID-19. However, much remains unknown about the accuracy of this technology in real-world settings, attitudes of potential users, and differences between delivery formats (mobile applications vs. carriable or wearable devices).

Objective: We pilot-tested two separate Bluetooth contact tracing technologies on a university campus to evaluate their sensitivity and specificity and to learn from the experiences of the participants.

Methods: We used a convergent mixed methods study design, and participants included graduate students and researchers working on a university campus during June-July 2020. We conducted separate two-week pilot studies for each Bluetooth technology, the first for a mobile phone application ("App Pilot") and the second for a small, electronic "tag" ("Tag Pilot"). Participants validated a list of Bluetooth-identified contacts daily and reported additional close contacts not identified by Bluetooth. We used these data to estimate sensitivity and specificity. Participants completed a post-participation survey regarding appropriateness, usability, acceptability, and adherence, and provided additional feedback via free text. We used tests of proportions to evaluate differences in survey responses between participants from each pilot, paired t-tests to measure differences between compatible survey questions, and qualitative analysis to evaluate the survey's free-text responses.

Results: Among the 25 participants in the App Pilot, 53 contact interactions were identified by Bluetooth and 61 by self-report. Among the 17 participants in the Tag Pilot, 171 contact interactions were identified via Bluetooth and four by self-report. The tag had significantly higher sensitivity compared to the app (46/49, 94% vs 35/61, 57%; $p<.001$), as well as higher specificity (120/126, 95% vs 123/141, 87%; $p=.02$). Most participants felt that Bluetooth contact tracing was appropriate on campus (26/32, 81%) while significantly fewer participants felt that using other technologies, such as GPS or Wi-Fi, was appropriate (17/31, 55%; $p=0.024$). Most participants preferred technology developed and managed by the university rather than a third party (27/32, 84%) and preferred not to have tracing applications on their personal phones (21/32, 66%), due to "concerns with privacy." There were no significant differences in self-reported adherence rates across pilots.

Conclusions: Convenient and carriable Bluetooth technology may improve tracing efficiency while alleviating privacy concerns by shifting data collection away from personal devices. With accuracy comparable to, and in this case superior to, mobile phone applications, such approaches may be suitable for workplace or school settings with the ability to purchase and maintain physical devices.

5.2 Introduction

Background

Following its identification in Wuhan, China in December 2019, SARS-CoV-2 rapidly spread across the globe resulting in millions of infections and deaths due to Coronavirus Disease 2019 (COVID-19) [1]. As health organizations throughout the world worked to develop adequate pharmaceutical therapies and vaccines, many public health agencies relied on non-pharmaceutical interventions to reduce community transmission of SARS-CoV-2. In particular, the world relied on mass-screening [2], lockdowns [2], physical distancing [3], mask wearing [4], and contact tracing [5]. While large-scale lockdowns and comprehensive masking interventions are less commonly seen in public health interventions, contact tracing is a traditional intervention that has proven effective in many other contexts [6-8]. However, the implementation of contact tracing for SARS-CoV-2 has faced many challenges due to high incidence rates even among asymptomatic individuals [9], pre-symptomatic transmission [10], and, in many places, a lack of staffing and infrastructure [11]. These challenges made it difficult in many settings to achieve the yield (proportion of cases and contacts interviewed, isolated, and/or quarantined) and timeliness (time from symptom onset or testing to isolation for cases, and time from exposure to quarantine for contacts) thought to be required for effectiveness [12, 13].

These challenges shifted the focus of many health agencies to mitigation (rather than containment) and led many to propose contact tracing innovations designed to make tracing more feasible [14]. While traditional contact tracing relies on interviewing cases and contacts in-person or by telephone, several countries augmented data collection using individual-level GPS data [15], Bluetooth technology [16], and other personalized data sources [17]. One technology in particular, Bluetooth, gained widespread attention in both the press [18] as well as scientific literature [19]. Despite the theoretical benefits of Bluetooth-assisted contact tracing and its implementation in various countries [16], the public health and lay communities are far from reaching consensus regarding the appropriateness [20] and effectiveness [21, 22] of this innovation, largely due to two reasons.

First, many have raised concerns about the loss of individual privacy associated with automated data collection methods such as Bluetooth-assisted tracing [23, 24]. In many countries, mandating participation in Bluetooth-assisted contact tracing is not feasible, and the effectiveness of this approach relies on a high user uptake among the population [22]. Implementation of Bluetooth-assisted tracing apps in non-mandated settings has so far been met with low uptake [25, 26], and therefore a better understanding of potential users' perceptions and privacy concerns is needed. Second, while research in other contexts has found various technologies including radio frequency detectors, Wi-Fi, and Bluetooth to be helpful in the detection of contact interactions [27-29], there are few studies evaluating the overall impact and effectiveness of Bluetooth-assisted tracing in the context of COVID-19 [30, 31]. Although it seems intuitive that Bluetooth-assisted data collection may lead to an increase in the total number of identified COVID-19 "close contacts" (defined by the Centers for Disease Control and Prevention (CDC) as in-person interactions within six feet for at least 15 minutes) and more rapid identification of these individuals, there is little real-world data to directly verify this nor to evaluate the accuracy of Bluetooth data [21, 30].

Goal of This Study

Together, doubts about the appropriateness and acceptability of Bluetooth-assisted contact tracing and the accuracy and reliability of these data pose challenges to implementation and adoption. Due to low vaccine uptake [32, 33] and breakthrough transmission by variant strains [34], overcoming these challenges is critical as contact tracing will remain a core part of the public health response to COVID-19 even in the post-vaccine phase of the pandemic. To address these knowledge gaps, we pilot-tested two different Bluetooth-assisted tracing technologies on a university campus, one which collected Bluetooth data using a mobile phone app and another that used a separate, carriable device ("tag") with Bluetooth functionality. Using a convergent mixed methods design, we measured the sensitivity and specificity of each Bluetooth technology and assessed participant perceptions regarding appropriateness, usability, acceptability, and adherence using a quantitative survey and qualitative free-text analysis.

5.3 Methods

Study Setting and Population

We conducted two separate pilot studies in June-July 2020 at a medium-sized private university in the US Northeast. During this time, only essential personnel and select individuals were allowed on campus with prior approval. Campus-wide precautions included mask wearing, physical distancing, daily symptom assessments and testing.

Study participants included graduate students and researchers working during this period; graduate students or researchers working from home were ineligible for participation. We recruited participants by emailing faculty members and lab supervisors who subsequently forwarded our recruitment emails to their students and research staff. We then selected labs with the highest acceptance rates. We also prioritized enrollment from labs that shared workspaces with other recruited labs. Due to the focused nature of the pilots, we did not collect demographic data from participants. The sequential pilots each lasted two weeks (14 days) starting on a Monday, and different labs participated in the separate pilots. Sample size was determined by availability of required study devices. The collected data were stored on secure university servers throughout the study and analysis period.

Pilot 1: Mobile Phone-Based Bluetooth

Technology

In the first pilot (hereafter referred to as the “App Pilot”) we evaluated a mobile phone application developed by the university’s ITS staff (Multimedia Appendix: Image 1). It functioned by detecting Bluetooth signals emitted by other phones that had the same app downloaded and activated. The app estimated distance between mobile phones based on signal strength while recording the duration of the interaction. The app also had functionality for users to enter a date of symptom onset or positive test, although this function was not used during the pilot. Data were automatically sent to a centralized server. The university provided Android phones to participants for the duration of the study so that they did not have to download the app on their personal devices.

Setting and Data Collection

All App Pilot participants were provided with written instructions describing how to install and use the mobile application, how to validate and report new contact interactions, and contact information for technical support if needed. Participants were asked to carry the study phone while on campus. At the end of each day, participants reviewed an online spreadsheet of their Bluetooth-identified close contacts and confirmed or denied each interaction. We also asked participants to identify additional contacts that were not detected by Bluetooth, and we subsequently removed any self-reported contacts who were not study participants. Participants were asked to use their best judgment when estimating the length of each interaction.

Pilot 2: Tag-Based Bluetooth

Technology

In the second pilot (hereafter referred to as the "Tag Pilot") we evaluated a carriable device ("tag") equipped with Bluetooth functionality, designed by author RM (Multimedia Appendix: Images 2A-B and 3). The tags recorded Bluetooth signals emitted from other tags, using signal strength to determine distance while recording duration of interactions. Data were stored locally on the tags and routinely synced to a central server by study participants using an app that paired with the participant's phone. The app only used Bluetooth to communicate with the tag while syncing and otherwise did not collect any additional data or use Bluetooth to communicate with any non-paired tags or other devices. The tag software additionally allows for contact interactions to be encrypted when recorded and stored in the central server, thereby anonymizing the data. When this feature is active, decrypting the data requires the user to provide permission by submitting a decryption token through the app. However, this feature was not enabled during the study so that we could determine all contact records for the purpose of evaluating the system's efficacy. Additional details regarding the tag's development can be found elsewhere [35]. The university provided participants with Android phones for the duration of the pilot to facilitate syncing of tag data. Participants were asked to use their best judgment when estimating the length of each interaction.

Setting and Data Collection

All Tag Pilot participants were provided with written instructions describing how to install and use the mobile syncing application, how to pair it with their Bluetooth tag, and how to validate and report new contact interactions, and contact information for technical support if needed. Participants were asked to carry the tag while on campus and to sync their Bluetooth data after each shift. At the end of each day, participants reviewed a list of their Bluetooth-identified close contacts and confirmed or denied each interaction using an online web interface. We also presented participants with the estimated duration of each recorded interaction and asked participants to report if the duration was under- or over-estimated. Similar to the App Pilot, we asked participants to identify additional contacts not detected by Bluetooth and subsequently removed those who were not study participants.

Post-Participation Survey

Following each pilot, we sent a survey to participants focusing on their experiences using the pilot technology as well as their perceptions regarding the appropriateness of technology-assisted tracing on campus (see Table 5.1 for survey domains). We adapted this survey from a previously validated mHealth usability questionnaire [36]. Most questions used a seven-point Likert scale ranging from *strong agreement* to *strong disagreement*, including a *neutral* response option. The survey also contained a free text question asking participants to provide any additional comments about their experience or suggestions about the technology. We used Cronbach's alpha to measure the reliability of our adapted scale after aligning the directionality of question responses. We excluded the free text response and two other scale items from the reliability measurement that asked participants to select various ways in which they carried the devices or reasons why they were not carried.

Table 5.1. Post-participation survey overview.

Domain	Sub-Domain (if applicable)	Goals Within Domain/Sub-Domain
Appropriateness		
	-	To measure participant perceptions about the appropriateness of Bluetooth contact tracing and the use of certain types of data (Bluetooth, GPS, Wi-Fi, etc.)
Usability		
	Ease of Use	To measure the ease with which participants install, learn to use, and use the apps.
	Interface and Satisfaction	To measure participant experiences and satisfaction with the design and interface of the app.
Acceptability		
	Usefulness	To evaluate participant beliefs surrounding the usefulness of the tracing technology.
	Coherence	To evaluate participants' understanding of how data are collected and protected by the technology.
	Social Influence	To measure the presence of social influence from peers or supervisors regarding uptake of technology-assisted tracing.
	Setting	To measure perceptions about available assistance for the use of the apps and/or devices and individual agency in uptake.
Adherence		
	-	To measure adherence and participant preferences with regard to carrying the study devices.

Analysis Plan

Quantitative Study Outcomes and Measurements

We used participants' daily contact validation responses to estimate the sensitivity and specificity of the two technologies (see Table 5.2 for outcome and measure definitions) and used two-tailed tests of proportions to compare these values between pilots. We also described the post-participation survey by presenting proportions of participants agreeing with each Likert question or selecting responses from other categorical questions as well as means for responses to continuous questions. We measured differences in survey responses between participants from different pilot groups using two-tailed tests of proportions for Likert agreement and categorical questions and unpaired, two-tailed t-tests for continuous questions. Additionally, we used paired tests of proportions to measure differences between agreement with several comparable survey questions, including (1) appropriateness of Bluetooth vs location data (GPS and/or Wi-Fi) for contact tracing, (2) peer vs. supervisor vocal support of study technology, and (3) peer vs. supervisor vocal concern about the study technology.

Table 5.2. Definitions of Bluetooth measures and outcomes.

	Measures/Outcomes	Definition
Measures[a]		
	True Positive	Bluetooth-identified contact that is confirmed by participant
	True Negative	No contacts detected, confirmed by participant
	False Positive	Bluetooth-identified contact denied by participant
	False Negative	Participant-recalled contact that was not detected by Bluetooth
Outcomes		
	Sensitivity	True Positive / (True Positive + False Negative)
	Specificity	True Negative / (True Negative + False Positive)

Legend: [a]15 minutes of interaction within six feet required to meet definition of "close contact". In addition to confirming/denying each close contact interaction, participants from the Tag Pilot were asked to comment on the under- or over-estimation of the recorded contact duration. We allowed a 5-minute window of error, within which a contact's measurement type could be altered. For example, a contact detected for 15-19 minutes would be designated as a false positive if the study participant noted that the interaction length was over-estimated, while a contact recorded for 10-14 minutes would be designated as a false negative if the study participant noted that the interaction length was under-estimated.

Qualitative Analysis of Free Text Responses

The coding team (TS, LG) used a codebook that was deductively based upon the survey topics. TS coded the free text responses, and the coding team met regularly to review the coded text and reach agreement on all coding decisions. The coding team also refined code definitions and generated new codes when applicable throughout the coding process. "RADaR," a rapid qualitative analysis approach [37], was used in which the coding and analysis were done in Microsoft Excel (Redmond, WA, USA) rather than in a traditional qualitative analysis software. We synthesized the qualitative and quantitative as part of the mixed methods analysis [38, 39] by identifying quotes that provided greater context or deeper understanding for the findings from the quantitative survey analyses. Selected quotes are presented alongside the quantitative findings within the relevant survey domains.

Human Rights Approval

This study was approved by the Yale Human Subjects Committee and written consent was obtained from participants prior to enrollment. We did not offer incentives for participations.

5.4 Results

Study Participants, Numbers of Shifts, and Frequencies of Contact Interactions

We invited 33 participants from 7 labs for the App Pilot, of which 30 agreed to participate, and 25 completed the two-week period of follow-up. 53 contact interactions were identified via Bluetooth and an additional 61 were reported by participant recall. We invited 24 participants from 2 labs for the Tag Pilot, of which 17 agreed to participate, and all completed the two-week period of follow-up. A defect was identified in the tag cases at the end of the first week of data collection that rendered the data unusable. The cases were then replaced, and only the data from the second study week were further analyzed. In the second week of data collection, 171 contact interactions were identified by Bluetooth and an additional four were reported by participant recall.

Sensitivity and Specificity

We present estimates of sensitivity and specificity and counts of true/false positives and negatives in Table 5.3, stratified by pilot. The tag had significantly higher sensitivity compared to the app (46/49, 94% vs 35/61, 57%; $p<.001$), as well as higher specificity (120/126, 95% vs 123/141, 87%; $p=.02$). Of note, three participants in the Tag Pilot reported leaving their tags on their desks during days on which they were not on-campus, resulting in false recordings of contact interactions. When these interactions are removed from the dataset, sensitivity and specificity become 93% (43/46) and 100% (111/111), respectively.

Table 5.3. True/false positive and negative counts with sensitivity/specificity estimates.

	Measures/Outcomes	App Pilot	Tag Pilot
Measures			
	True Positive	35	46
	True Negative	123	120
	False Positive	18	6
	False Negative	26	3
Outcomes			
	Sensitivity	57%	94% (93*%*)[a]
	Specificity	87%	95% (*100%*)[a]

Legend: [a]Adjusted values after removing erroneous contact records from tags left on participant desks when they were not on campus

Post-Participation Survey

Twenty participants from the App Pilot and 12 participants from the Tag Pilot completed the post-participation survey (Cronbach's alpha = 0.90). Below, we present the quantitative results from each section alongside qualitative findings when applicable.

Appropriateness

Overall, there were no differences in perceived appropriateness of technology-assisted tracing among participants between pilot groups (Table 5.4). Most participants felt that contact tracing via Bluetooth was appropriate but felt that the use of additional location data such as GPS or Wi-Fi was less appropriate (26/32, 81% approval for Bluetooth vs 17/31, 55% approval for GPS/Wi-Fi; $p = 0.024$). Most participants also preferred technology developed and managed by the university rather than a third party (27/32, 84%) and preferred to not download apps on their personal devices (21/32, 66%).

Table 5.4. Post-Participation Survey: Appropriateness Domain

Questions	Total % Agreement[a] (n=32)[b]	App % Agreement[a] *(n=20)[b]*	Tag % Agreement[a] *(n=12)[b]*	P-value[c]
It is appropriate for the University to use Bluetooth apps to monitor interactions on campus in order to more efficiently perform contact tracing.	81 (26/32)	80 (16/20)	83 (10/12)	0.815
It is appropriate to use location information such as GPS and Wi-Fi connection data for contact tracing.	55 (17/31)	58 (11/19)	50 (6/12)	0.667
I would prefer to use a contact tracing app on a university-owned device as opposed to downloading the app on my personal phone.	66 (21/32)	65 (13/20)	67 (8/12)	0.923
I would prefer to use an app developed and owned by the University as opposed to an app developed and owned by an independent third party.	84 (27/32)	85 (17/20)	83 (10/12)	0.900
I have concerns about how using this app, or an app like it, could affect my privacy.	75 (24/32)	70 (14/20)	83 (10/12)	0.399

Legend: [a]Percentage agreement was calculated by dividing the number of Likert responses indicating agreement by the total number of Likert responses for each question. [b]Some questions were not answered by all participants; exact counts of agreement and total responses are shown in parentheses for each question. [c]P-values obtained using tests of proportions to evaluate differences between pilots.

Regardless of the approach, most participants (24/32, 75%), though not all, reported concerns about how their privacy would be protected, and these concerns were expanded upon in the free-text data.

> *"One [lab member] voiced concerns about how individual GPS contact data might be used against individuals (such as by police in the case of protests) - sadly, similar to what actually happened with a Mayor releasing names publicly recently....I think if the privacy aspect is addressed VERY clearly and intentionally it might increase the acceptance." (App Pilot, Participant 3)*

> *"I do have some concerns with privacy, but I am not sophisticated enough in this topic to articulate my concerns or to understand if I should be concerned or not. I think the data from a school-wide system does have the potential to be abused, but I think an effective contact tracing system should/could significantly increase the safety of students, faculty, and staff on campus." (Tag Pilot, Participant 17)*

Usability

There were no observed differences between pilot groups regarding app usability (Table 5.5), and most participants from both pilots felt their respective apps were easy to install (25/31, 81%) and use (31/32, 97%). They also reported moderate levels of satisfaction with the app interfaces (21/32, 66%) and feedback from the apps (18/31, 58%). The amount of time required to use the apps was acceptable to most (29/32, 91%), and overall satisfaction was high (26/32, 81%). However, several participants from both pilots described difficulties downloading and installing apps, syncing tags to mobile devices for uploading data, discerning how the app was responding to the user due to unclear feedback from the app, or experiencing other technological glitches.

> *"[The app] would switch tracking off by itself."* (App Pilot, Participant 13)

> *"When I first obtained the phone, there was no contact tracing app on it, and I could not find a way to download it…When I tried syncing the tag to the phone, there was never a message telling me that the tag was synced, only 'connecting' and 'communicating.'"* (Tag Pilot, Participant 19)

Table 5.5. Post-Participation Survey: Usability Domain

Sub-Domains	Questions	Total % Agreement[a] (n=32)[b]	App % Agreement[a] *(n=20)[b]*	Tag % Agreement[a] *(n=12)[b]*	P-value[c]
Ease of Use					
	It was easy for me to install the app on the device.	81 (25/31)	84 (16/19)	75 (9/12)	0.527
	It was easy for me to learn to use the app.	97 (31/32)	95 (19/20)	100 (12/12)	0.431
	The app was easy to use.	97 (31/32)	95 (19/20)	100 (12/12)	0.431
Interface and Satisfaction					
	I like the interface of the app.	66 (21/32)	65 (13/20)	66 (8/12)	0.923
	The information in the app was well organized, so I could easily find the information I needed.	71 (22/31)	63 (12/19)	83 (10/12)	0.228
	The app adequately acknowledged and provided information to let me know the progress of my action.	58 (18/31)	53 (10/19)	66 (8/12)	0.441
	The amount of time involved in using the app is acceptable.	91 (29/32)	85 (17/20)	100 (12/12)	0.159
	I would use this system again.	78 (25/32)	70 (14/20)	92 (11/12)	0.151
	Overall, I am satisfied with this system.	81 (26/32)	80 (16/20)	83 (10/12)	0.815

Legend: [a]Percentage agreement was calculated by dividing the number of Likert responses indicating agreement by the total number of Likert responses for each question. [b]Some questions were not answered by all participants; exact counts of agreement and total responses are shown in parentheses for each question. [c]P-values obtained using tests of proportions to evaluate differences between pilots.

Acceptability

Most participants felt that their respective app or tag would be useful for contact tracing (25/31, 81%), though a lack of consistency between recalled interactions and Bluetooth data diminished some participants' confidence in the technology.

> *"The device initially failed to detect other devices, and therefore I'm worried about the efficiency of the app." (App Pilot, Participant 7)*

> *"I think that when it worked, it was great. There were times, such as my first day, where it didn't detect anyone even though I was well within 6 feet." (Tag Pilot, Participant 15)*

Most participants understood how their respective device collected (27/32, 84%) and protected their data (22/32, 69%) (Table 5.6). With regard to social influence and study setting, there were no significant differences between pilot environments. Across both pilots, participants more frequently reported vocal support for the technology from supervisors than from peers (21/26, 81% from supervisors vs. 10/27, 37% from peers; $p = 0.001$). The opposite was true regarding vocal concern, with participants more frequently reporting vocal concern from peers compared to supervisors (13/29, 45% from peers vs. 2/25, 8% from supervisors; $p = .003$). Within the study environment, most participants felt that adequate technical assistance was available when needed (20/28, 71%), and also felt that, should the university adopt such technology, they would maintain individual agency over whether or not they used the devices (26/31, 84%).

Table 5.6. Post-Participation Survey: Acceptability Domain

Sub-Domains	Questions	Total % Agreement[a] (n=32)[b]	App % Agreement[a] *(n=20)[b]*	Tag % Agreement[a] *(n=12)[b]*	P-value[c]
Usefulness					
	The system would be useful for contact tracing.	81 (25/31)	74 (14/19)	92 (11/12)	0.217
	The app has all the functions and capabilities I expected it to have.	58 (18/31)	42 (8/19)	83 (10/12)	**0.024**
Coherence					
	I understand how data collected with this system would be used for contact tracing.	84 (27/32)	80 (16/20)	92 (11/12)	0.379
	I understand how this system currently protects my privacy.	69 (22/32)	65 (13/20)	75 (9/12)	0.555
Social Influence					
	Peers whose opinions I value have vocalized their support for this system.	37 (10/27)	24 (4/17)	60 (6/10)	0.058
	Supervisors in my workplace have vocalized their support for this system.	81 (21/26)	83 (15/18)	75 (6/8)	0.619
	Peers whose opinions I value have voiced concerns about using this system.	45 (13/29)	50 (9/18)	36 (4/11)	0.474
	Supervisors in my workplace have voiced concerns about using this system.	8 (2/25)	12 (2/17)	0 (0/8)	0.312
Setting					
	Technical assistance was available when needed.	71 (20/28)	71 (12/17)	73 (8/11)	0.903
	The decision to use or not use this system will remain under my control.	84 (26/31)	79 (15/19)	92 (11/12)	0.348

Legend: [a]Percentage agreement was calculated by dividing the number of Likert responses indicating agreement by the total number of Likert responses for each question. [b]Some questions were not answered by all participants; exact counts of agreement and total responses are shown in parentheses for each question. [c]P-values obtained using tests of proportions to evaluate differences between pilots.

Adherence

There was no difference between pilots in overall adherence rates based on self-reported percentages of shifts during which the study device was carried (mean=87%) (Table 5.7), although participants in the Tag Pilot more commonly reported that their study device was convenient to carry than did participants from the App Pilot (Tag Pilot = 11/12, 92% vs. App Pilot = 11/20, 55%; $p = 0.030$). While some participants from the App Pilot reported leaving the device at home (2/13, 15%), participants from both pilots reported that the most common reason for not carrying the devices was forgetting it at a workstation (17/23, 74%). App Pilot participants also reported inabilities to carry the study device into certain lab environments (App Pilot = 5/13, 38% vs. Tag Pilot = 0/10, 0%; $p = .027$), while Tag Pilot participants reported that charging the device interfered with adherence (Tag Pilot = 3/10, 30% vs. App Pilot = 0/13, 0%; $p = 0.034$).

Table 5.7. Post-Participation Survey: Adherence Domain

Questions	**Total % Agreement[a,b] (n=32)[c]**	**App % Agreement[a,b] *(n=20)*[c]**	**Tag % Agreement[a,b] *(n=12)*[c]**	**P-value[d]**
Over the course of the two-week study period, for what proportion of your total work shifts did you have the device either on you or within arms' reach?	87[e]	91[e]	81[e]	0.056
The device was convenient to carry with me throughout my work shifts.	69 (22/32)	55 (11/20)	92 (11/12)	**0.030**
How did you carry the device with you throughout your workday? [*Tag-only*] • Pocket • Bag • Belt/lanyard • Left at workspace	N/A	N/A	• 92 (11/12) • 0 (0/12) • 8 (1/12) • 8 (1/12)	N/A
What were the most common reasons why you would not carry the device with you during a work shift? • Forgot at home • Intentionally left at home • Forgot at desk/workstation • Intentionally left at desk/workstation • Unable to carry it into certain lab environments • Left it to charge	• 9 (2/23) • 0 (0/23) • 74 (17/23) • 9 (2/23) • 22 (5/23) • 13 (3/23)	• 15 (2/13) • 0 (0/13) • 69 (9/13) • 15 (2/13) • 38 (5/13) • 0 (0/13)	• 0 (0/10) • 0 (0/10) • 0 (8/10) • 0 (0/10) • 0 (0/10) • 30 (3/10)	• 0.194 • - • 0.560 • 0.194 • **0.027** • **0.034**
I would be more likely to carry the device with me if it were smaller (for instance, the size of a thumb drive that could be attached to a lanyard). [*App-only*]	N/A	95 (19/20)	N/A	**<0.0001**
I would be more likely to carry the tag with me if it were larger (for instance,	N/A	N/A	0 (0/12)	

the size of a phone). [*Tag-only*]				

Legend: [a]Unless otherwise specified [b]Percentage agreement was calculated by dividing the number of Likert or binary responses indicating agreement by the total number of responses for each question. [c]Some questions were not answered by all participants; exact counts of agreement and total responses are shown in parentheses for each question. [d]P-values obtained by tests of proportions for differences in percentage agreement and by unpaired, t-test for differences in means. [e]Mean response

Many participants from the App Pilot used the free text response to note the inconvenience of carrying an additional phone and suggested that a smaller device be used. A minority suggested that they be allowed to download the tracing app directly on their personal phones. Gender-specific difficulties in carrying the App Pilot study phone were also noted by one participant, while a separate participant from the Tag Pilot noted the relative ease of carrying the tag.

> *"The only problem I found with this [study phone] is that it is big. For women it just does not fit in the front pocket of the jeans and in the summer, you are not wearing a jacket under your lab coat. So, the only place left is the pocket of the jeans in the back. And that is a bit uncomfortable when you sit down, or you are scared it might fall out. I also do not feel good putting it in the pockets of my lab coat because I consider them "dirty" and I do not want to have lab dirt in my home, or touch it without gloves. So, it would be much more convenient if it would be a bracelet or a watch or something around those lines." (App Pilot, Participant 12)*

> *"The shape of [the tag] is pretty clunky to carry around, but as long as you wear pants with pockets it's easy enough to just wear in your back pocket." (Tag Pilot, Participant 16)*

The vast majority of participants from the App Pilot reported that they would be more likely to carry a Bluetooth device if it were smaller than a phone (19/20, 95%), while no participants from the Tag Pilot (0/12, 0%) agreed that increasing the size of the tag would increase adherence ($p<0.0001$), indicating an overall preference for smaller devices.

5.5 Discussion

Incomplete vaccine uptake [32, 33] and potential for breakthrough transmission due to new variants [34] suggest that contact tracing will remain an important tool in the ongoing response to COVID-19. However, its use thus far in the pandemic has revealed many challenges to scaling-up traditional contact tracing [40-43] and identified a need to improve upon existing methods. Digital contact tracing tools offer many opportunities to improve the impact of contact tracing [44], and increasing our understanding of how different technologies may be applied for this purpose is critical. In our dual-pilot evaluation of two novel contact tracing technologies, we found that Bluetooth contact tracing was perceived as appropriate to the majority of study participants, adherence to device carrying was high, and participants were largely satisfied with their experiences. However, most participants still reported concerns about privacy, and both technologies encountered occasional technical glitches. Importantly, we also found that the tag-based device was easier to carry and had superior sensitivity and specificity. These increased performance metrics may have been due to differences between the Bluetooth signal strength settings of each technology or in how participants carried the different study devices, as reflected in the post-participation survey.

Our findings are similar to a recent study [45] that compared a Bluetooth mobile app to a wearable, radio frequency-based, real-time locator device within a healthcare setting. The researchers found the wearable device to be superior to Singapore's "TraceTogether" app with regard to sensitivity and specificity, and also found that the app's performance was worse on iPhones compared to Android devices. In a similar study, the wearable device was compared to electronic medical record-assisted tracing and was again found to be superior [46]. Our study builds upon these findings by evaluating similar app-based technology in a new, university setting, while also comparing it directly to a novel Bluetooth tag device, rather than a radio frequency-based device.

Although most proximity-based contact tracing technologies offer similar benefits, such as the ability to identify unknown contacts or customize detection thresholds based on evolving knowledge of transmission dynamics [47], different approaches (e.g., app vs. carriable device) offer certain additional benefits and drawbacks. Below, we discuss key differences while paying heed to the importance of context. While traditional contact tracing focuses on community and population transmission, COVID-19 has led many closed-door environments, such as workplaces, schools, universities, and hospitals to conduct contact tracing independently from, or in partnership with, local public health systems [48, 49]. The differences between community and closed-door tracing are important when comparing app-based and tag-based systems, as different contexts are often coupled with different funding capacities, thresholds for acceptable uptake of tracing technology, and user privacy concerns.

Deploying Bluetooth tracing technology to communities or populations at large is likely only feasible using an app-based system. App-based tracing technologies, such as those developed by Apple and Google, have already been deployed throughout the globe [16] including in many US states [26], with relatively little cost to distribution beyond social marketing. Meanwhile, it would not be logistically or financially feasible to deploy a similar number of tag devices throughout the entire population, as each tag costs approximately $10. Furthermore, while updating apps is relatively seamless, updating hardware poses a greater challenge, as we encountered in this study when we discovered a defect in our tag cases. Despite these potential drawbacks, tags and similar approaches may be more feasible in closed-door environments that have available funding to spend on the protection of a much smaller population.

Acceptable thresholds for uptake may also differ between environments, making the logistical concerns noted above more or less important across different settings. Public health officials in many countries are often hesitant or unable to mandate participation in health interventions, as demonstrated with mask policies in response to COVID-19 [50]. Public health programs also frequently lack funding to properly incentivize participation. As a result, population-wide uptake of app-based technology for tracing will likely always be limited. Closed-door environments, on the other hand, may face greater pressure to standardize and ensure the safety of all staff, students, or workers, and therefore may prioritize, or mandate, comprehensive uptake, as demonstrated by many universities requiring vaccination for all students [51]. However, reaching such high uptake of digital contact tracing without diminishing individual agency or ignoring privacy concerns poses a challenge.

Privacy concerns are often related to the types of information collected as well as the organization or government collecting the data [23, 24], and may be heightened in the context of a pandemic [52]. Notably, our study participants felt that using Bluetooth data for tracing was more appropriate than GPS or Wi-Fi data. While technologies such as blockchain may increase the security of app-based approaches [53] and further reduce the risks of data leakage, effectively communicating such methods and establishing trust with potential users may remain difficult as long as data collection relies on personal devices, as reflected by our participants' preferences against using apps on their phones. This provides several arguments for shifting data collection away from personal devices and onto organization-owned tracing tags when possible. First, the tag-based system offers users in closed-door environments the opportunity to participate in contact tracing without requiring data collection on their phones. While our study still relied on an app to sync the tag's data, the provision of "syncing stations" throughout closed-door environments could eliminate the need for an app entirely and further reduce concerns about leakage of personal phone data. Second, the use of organization-owned tags addresses concerns about governments or third-party companies accessing personal data [23, 52], which was reflected in our participants' preferences against third party apps. Ultimately, these features offer the potential to reduce privacy concerns and increase uptake within closed-door environments.

There are several key strengths to this study, including its use and evaluation of novel technologies developed directly in response to the COVID-19 pandemic. Second, the setting in which the study was conducted is typical of some other environments, in particular schools and universities, that have struggled to perform contact tracing throughout the pandemic, making this study increasingly relevant to public health practitioners or researchers operating in similar environments. Last, the use of mixed methods, including sensitivity and specificity estimations, survey analyses, and qualitative analysis, allowed us to triangulate our findings and present a layered evaluation of the technologies' performance metrics as well as the users' experiences.

There are also several important limitations to this study. First, the sample size was relatively small, increasing the risk of Type II errors. Second, the recruitment of different labs and participants for each pilot creates some uncertainty about the mechanisms driving observed differences in Bluetooth performance metrics and user experiences or perceptions. However, the lack of significant differences in survey responses regarding setting and social influences, as well as the baseline similarities in lab environments selected for the study minimize this risk. Third, the lack of a true "gold standard" measurement for close contact interactions introduces potential for bias in the estimations of sensitivity and specificity. In particular, recall bias may have led to misreporting of self-report contacts, and the lack of precise measurements for the length of self-report interactions between participants may have introduced additional uncertainties. However, participants' daily review and validation of contact interactions likely minimized the potential for recall bias which would have been more severe if the data were collected less frequently. Furthermore, these potential biases likely affected each pilot similarly which lessens the degree to which such biases may have affected the comparisons between pilots. Fourth, based upon the participant-initiated method of qualitative data collection (optional free text box vs. traditional interview queries) it is doubtful that meaning saturation was achieved [54] and likely that themes would have been better explicated and perhaps more abundant if a traditional approach to qualitative interviewing had been used. Nonetheless, the study provides preliminary evidence about the relative merits of the two technologies that can inform larger studies in the future. Fifth, demographic data was not collected from participants at the time of recruitment, limiting our ability to evaluate differences across participant characteristics. Considering the small sample size and short timeframe of the pilots, we lacked statistical power to evaluate differences across participant characteristics and therefore did not include this as a study goal. Last, the relative homogeneity of the study sample may limit the generalizability of our findings to other non-University contexts which may feature differences in behavior, familiarity with technology, and/or attitudes [55].

In conclusion, as vaccine uptake remains non-comprehensive and new variants appear, contact tracing will remain a pillar of the public health response to COVID-19. Increasing the efficiency of contact tracing through adoption of technologies such as those evaluated here may improve its impact and ability to prevent or control outbreaks. This is among the first studies to directly evaluate the performance metrics of novel Bluetooth technologies when used for COVID-19 contact tracing in conjunction with evaluations of user experiences. Our participants found Bluetooth-assisted tracing to be appropriate, and we note several key differences between app-based and tag-based approaches. Benefits of the app-based system include its low cost and theoretical ease of mass distribution; drawbacks include increased privacy concerns of users. Benefits of the tag system include its superior sensitivity and specificity, ease of carrying the tag, and the potential to alleviate user privacy concerns; drawbacks include its reliance on hardware that may be less feasible to deploy in certain settings.

5.6 References

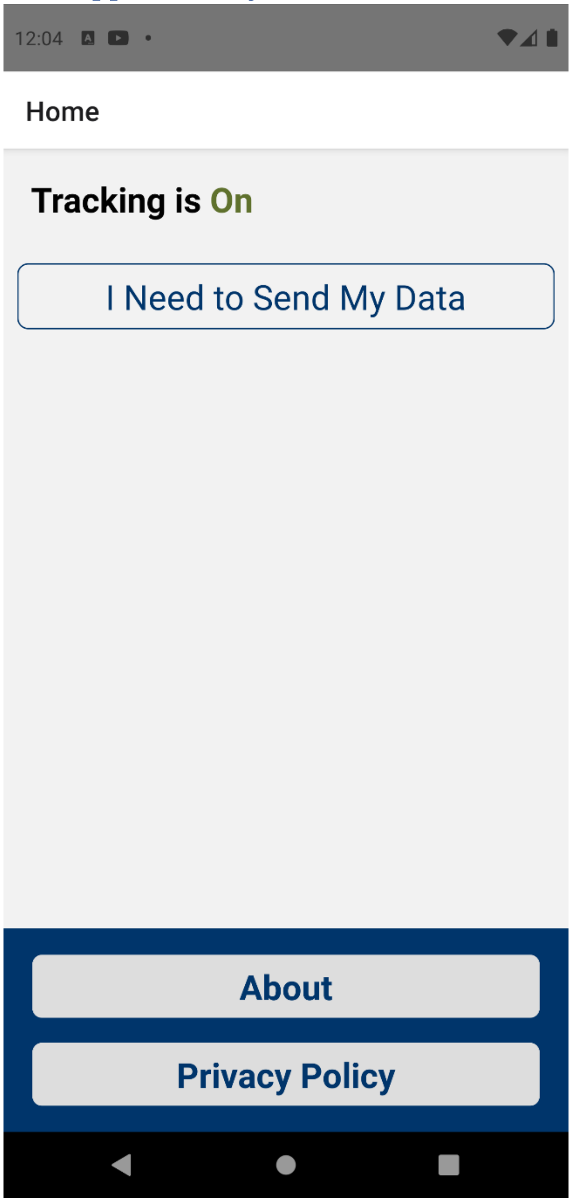
1. Keni R, Alexander A, Nayak PG, Mudgal J, Nandakumar K. COVID-19: Emergence, Spread, Possible Treatments, and Global Burden. Front Public Health. 2020;8:216.
2. Johanna N, Citrawijaya H, Wangge G. Mass screening vs lockdown vs combination of both to control COVID-19: A systematic review. J Public Health Res. 2020;9(4):2011.
3. Chu DK, Akl EA, Duda S, Solo K, Yaacoub S, Schunemann HJ, et al. Physical distancing, face masks, and eye protection to prevent person-to-person transmission of SARS-CoV-2 and COVID-19: a systematic review and meta-analysis. Lancet. 2020;395(10242):1973-87.
4. Van Dyke ME, Rogers TM, Pevzner E, Satterwhite CL, Shah HB, Beckman WJ, et al. Trends in County-Level COVID-19 Incidence in Counties With and Without a Mask Mandate - Kansas, June 1-August 23, 2020. MMWR Morb Mortal Wkly Rep. 2020;69(47):1777-81.
5. Yalaman A, Basbug G, Elgin C, Galvani AP. Cross-country evidence on the association between contact tracing and COVID-19 case fatality rates. Sci Rep. 2021;11(1):2145.
6. Ooi PL, Lim S, Chew SK. Use of quarantine in the control of SARS in Singapore. Am J Infect Control. 2005;33(5):252-7.
7. Mahachi N, Muchedzi A, Tafuma TA, Mawora P, Kariuki L, Semo BW, et al. Sustained high HIV case-finding through index testing and partner notification services: experiences from three provinces in Zimbabwe. J Int AIDS Soc. 2019;22 Suppl 3:e25321.
8. Fox GJ, Barry SE, Britton WJ, Marks GB. Contact investigation for tuberculosis: a systematic review and meta-analysis. Eur Respir J. 2013;41(1):140-56.
9. Al-Sadeq DW, Nasrallah GK. The incidence of the novel coronavirus SARS-CoV-2 among asymptomatic patients: A systematic review. Int J Infect Dis. 2020;98:372-80.
10. Bi Q, Wu Y, Mei S, Ye C, Zou X, Zhang Z, et al. Epidemiology and transmission of COVID-19 in 391 cases and 1286 of their close contacts in Shenzhen, China: a retrospective cohort study. Lancet Infect Dis. 2020;20(8):911-9.
11. Clark E, Chiao EY, Amirian ES. Why contact tracing efforts have failed to curb COVID-19 transmission in much of the U.S. Clin Infect Dis. 2020.
12. Prioritizing COVID-19 Contact Tracing Mathematical Modeling Methods and Findings 2020 [March 29, 2021]. Available from: https://www.cdc.gov/coronavirus/2019-ncov/php/contact-tracing/contact-tracing-plan/prioritization/mathematicalmodeling.html.
13. Ferretti L, Wymant C, Kendall M, Zhao L, Nurtay A, Abeler-Dorner L, et al. Quantifying SARS-CoV-2 transmission suggests epidemic control with digital contact tracing. Science. 2020;368(6491):eabb6936.
14. He W, Zhang ZJ, Li W. Information technology solutions, challenges, and suggestions for tackling the COVID-19 pandemic. Int J Inf Manage. 2021;57:102287.
15. Covid-19 National Emergency Response Center E, Case Management Team KCfDC, Prevention. Contact Transmission of COVID-19 in South Korea: Novel

Investigation Techniques for Tracing Contacts. Osong Public Health Res Perspect. 2020;11(1):60-3.
16. Kleinman RA, Merkel C. Digital contact tracing for COVID-19. CMAJ. 2020;192(24):E653-E6.
17. Jian SW, Cheng HY, Huang XT, Liu DP. Contact tracing with digital assistance in Taiwan's COVID-19 outbreak response. Int J Infect Dis. 2020;101:348-52.
18. Fowler GA. A covid-fighting tool is buried in your phone. Turn it on. The Washington Post2021 [March 29, 2021]. Available from: https://www.washingtonpost.com/technology/2020/11/18/coronavirus-app-exposure-alerts/.
19. Abeler J, Backer M, Buermeyer U, Zillessen H. COVID-19 Contact Tracing and Data Protection Can Go Together. JMIR Mhealth Uhealth. 2020;8(4):e19359.
20. Maccari L, Cagno V. Do we need a contact tracing app? Comput Commun. 2021;166:9-18.
21. Cebrian M. The past, present and future of digital contact tracing. Nature Electronics. 2021;4(1):2-4.
22. Almagor J, Picascia S. Exploring the effectiveness of a COVID-19 contact tracing app using an agent-based model. Sci Rep. 2020;10(1):22235.
23. Altmann S, Milsom L, Zillessen H, Blasone R, Gerdon F, Bach R, et al. Acceptability of App-Based Contact Tracing for COVID-19: Cross-Country Survey Study. JMIR Mhealth Uhealth. 2020;8(8):e19857.
24. Garrett PM, White JP, Lewandowsky S, Kashima Y, Perfors A, Little DR, et al. The acceptability and uptake of smartphone tracking for COVID-19 in Australia. PLoS One. 2021;16(1):e0244827.
25. Garza Adl. Contact Tracing Apps Were Big Tech's Best Idea for Fighting COVID-19. Why Haven't They Helped? Time2020 [March 29, 2021]. Available from: https://time.com/5905772/covid-19-contact-tracing-apps/.
26. State Approaches to Contact Tracing during the COVID-19 Pandemic 2021 [March 29, 2021]. Available from: https://www.nashp.org/state-approaches-to-contact-tracing-covid-19/.
27. Smieszek T, Barclay VC, Seeni I, Rainey JJ, Gao H, Uzicanin A, et al. How should social mixing be measured: comparing web-based survey and sensor-based methods. BMC Infectious Diseases. 2014;14(1):136.
28. Eagle N, Pentland AS, Lazer D. Inferring friendship network structure by using mobile phone data. Proc Natl Acad Sci U S A. 2009;106(36):15274-8.
29. Stehle J, Voirin N, Barrat A, Cattuto C, Isella L, Pinton JF, et al. High-resolution measurements of face-to-face contact patterns in a primary school. PLoS One. 2011;6(8):e23176.
30. Braithwaite I, Callender T, Bullock M, Aldridge RW. Automated and partly automated contact tracing: a systematic review to inform the control of COVID-19. Lancet Digit Health. 2020;2(11):e607-e21.
31. Digital Contact Tracing Tools Centers for Disease Control and Prevention2020 [May 26, 2021]. Available from: https://www.cdc.gov/coronavirus/2019-ncov/php/contact-tracing/contact-tracing-plan/digital-contact-tracing-tools.html.
32. Harrison EA, Wu JW. Vaccine confidence in the time of COVID-19. Eur J Epidemiol. 2020;35(4):325-30.

33. See How Vaccinations Are Going in Your County and State The New York Times [June 6 2021]. Available from: https://www.nytimes.com/interactive/2020/us/covid-19-vaccine-doses.html.
34. Rubin R. COVID-19 Vaccines vs Variants-Determining How Much Immunity Is Enough. JAMA. 2021;325(13):1241-3.
35. Manohar N, Manohar P, Manohar R. HABIT: Hardware-Assisted Bluetooth-based Infection Tracking. Cryptology ePrint Archive, Report 2020/949 (https://nam12safelinksprotectionoutlookcom/?url=https%3A%2F%2Fiacr%2F2020%2F949&data=04%7C01%7Ctylershelby%40yaleedu%7C9656b4b813fa480e8ad608d96322d673%7Cdd8cbebb21394df8b4114e3e87abeb5c%7C0%7C0%7C637649823534250757%7CUnknown%7CTWFpbGZsb3d8eyJWIjoiMC4wLjAwMDAiLCJQIjoiV2luMzIiLCJBTiI6Ik1haWwiLCJXVCI6Mn0%3D%7C1000&sdata=KqIXY1v1HFJMlftG8%2FNios5mf0kdmFHUwMBsD7jBK9Y%3D&reserved=0 <https://iacr/2020/949>). 2020.
36. Zhou L, Bao J, Setiawan IMA, Saptono A, Parmanto B. The mHealth App Usability Questionnaire (MAUQ): Development and Validation Study. JMIR Mhealth Uhealth. 2019;7(4):e11500.
37. Watkins DC. Rapid and Rigorous Qualitative Data Analysis:The “RADaR” Technique for Applied Research. International Journal of Qualitative Methods. 2017;16(1):1609406917712131.
38. Creswell JW, Clark VLP. Designing and Conducting Mixed Methods Research. Third ed: SAGE Publications, Inc; 2017.
39. Guetterman TC, Fetters MD, Creswell JW. Integrating Quantitative and Qualitative Results in Health Science Mixed Methods Research Through Joint Displays. Ann Fam Med. 2015;13(6):554-61.
40. Lash RR, Donovan CV, Fleischauer AT, Moore ZS, Harris G, Hayes S, et al. COVID-19 Contact Tracing in Two Counties - North Carolina, June-July 2020. MMWR Morb Mortal Wkly Rep. 2020;69(38):1360-3.
41. Sachdev DD, Brosnan HK, Reid MJA, Kirian M, Cohen SE, Nguyen TQ, et al. Outcomes of Contact Tracing in San Francisco, California—Test and Trace During Shelter-in-Place. JAMA Internal Medicine. 2021;181(3):381-3.
42. Lash RR, Moonan PK, Byers BL, Bonacci RA, Bonner KE, Donahue M, et al. COVID-19 Case Investigation and Contact Tracing in the US, 2020. JAMA Network Open. 2021;4(6):e2115850-e.
43. Lewis D. Why many countries failed at COVID contact-tracing — but some got it right. Nature. 2020;588(7838):384-7.
44. Zeng K, Bernardo SN, Havins WE. The Use of Digital Tools to Mitigate the COVID-19 Pandemic: Comparative Retrospective Study of Six Countries. JMIR Public Health Surveill. 2020;6(4):e24598.
45. Huang Z, Guo H, Lee YM, Ho EC, Ang H, Chow A. Performance of Digital Contact Tracing Tools for COVID-19 Response in Singapore: Cross-Sectional Study. JMIR Mhealth Uhealth. 2020;8(10):e23148.
46. Ho HJ, Zhang ZX, Huang Z, Aung AH, Lim WY, Chow A. Use of a Real-Time Locating System for Contact Tracing of Health Care Workers During the COVID-19 Pandemic at an Infectious Disease Center in Singapore: Validation Study. J Med Internet Res. 2020;22(5):e19437.

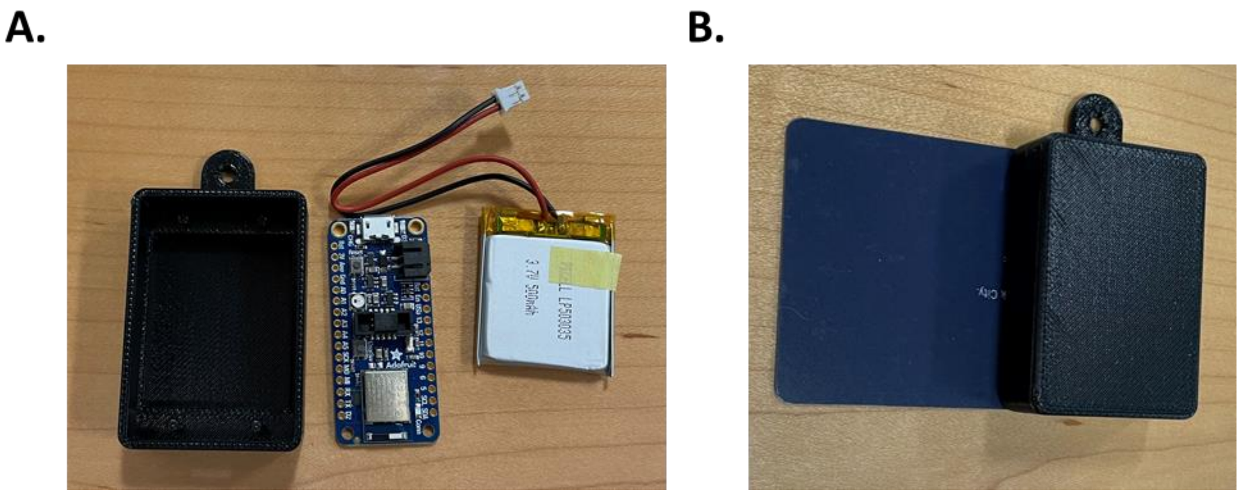
47. Bazant MZ, Bush JWM. A guideline to limit indoor airborne transmission of COVID-19. Proc Natl Acad Sci U S A. 2021;118(17):e2018995118.
48. Case Investigation and Contact Tracing in Non-healthcare Workplaces: Information for Employers Centers for Disease Control and Prevention (CDC)2020 [March 29, 2021]. Available from: https://www.cdc.gov/coronavirus/2019-ncov/community/contact-tracing-nonhealthcare-workplaces.html.
49. Interim Guidance for Case Investigation and Contact Tracing in K-12 Schools Centers for Disease Control and Prevention (CDC)2020 [March 29, 2021]. Available from: https://www.cdc.gov/coronavirus/2019-ncov/community/schools-childcare/contact-tracing.html.
50. Guzman-Cottrill JA, Malani AN, Weber DJ, Babcock H, Haessler SD, Hayden MK, et al. Local, state and federal face mask mandates during the COVID-19 pandemic. Infect Control Hosp Epidemiol. 2021;42(4):455-6.
51. Queen CS, Allen J. 100 U.S. colleges will require vaccinations to attend in-person classes in the fall. New York Times2021 [May 26, 2021]. Available from: https://www.nytimes.com/2021/04/29/us/colleges-vaccinations-enrollment.html.
52. Chan EY, Saqib NU. Privacy concerns can explain unwillingness to download and use contact tracing apps when COVID-19 concerns are high. Comput Human Behav. 2021;119:106718.
53. Idrees SM, Nowostawski M, Jameel R. Blockchain-Based Digital Contact Tracing Apps for COVID-19 Pandemic Management: Issues, Challenges, Solutions, and Future Directions. JMIR Med Inform. 2021;9(2):e25245.
54. Hennink MM, Kaiser BN, Marconi VC. Code Saturation Versus Meaning Saturation: How Many Interviews Are Enough? Qual Health Res. 2017;27(4):591-608.
55. Bente BE, van 't Klooster J, Schreijer MA, Berkemeier L, van Gend JE, Slijkhuis PJH, et al. The Dutch COVID-19 Contact Tracing App (the CoronaMelder): Usability Study. JMIR Form Res. 2021;5(3):e27882.

5.7 Supplementary Information



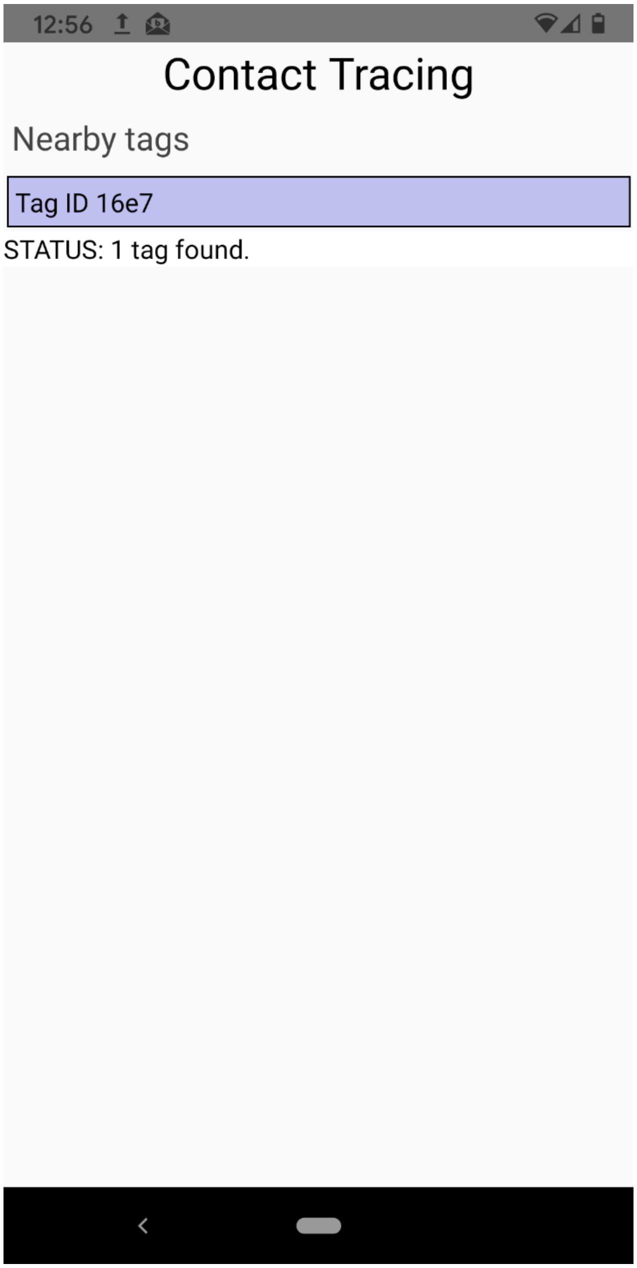
Supplementary Image 5.1: Screenshot of App Pilot mobile application

Legend: This image contains a screenshot of the contact tracing mobile app used in the App Pilot.



Supplementary Images 5.2A and 5.2B: Bluetooth device ("tag") used in the Tag Pilot

Legend: These images display the tag components (2A) and the assembled tag alongside a typical gift card for size comparison (2B). Tag dimensions were roughly 6cm x 3.8cm x 1.6cm.



Supplementary Image 5.3: Screenshot of Tag Pilot mobile syncing application

Legend: This image displays a screenshot of the syncing application used by participants in the Tag Pilot. To sync the data from their tag to the central servers, participants held the tag near the phone until it was detected by the mobile app (as shown in the blue stripe above), and then "pressed" on the Tag ID shown.

Chapter Six. Implications and Conclusions

Table 6.1 and other select content from this chapter have been previously submitted for peer review as*:*

Tyler Shelby, Brian Weeks, Maritza Bond, Lauretta E. Grau, Marcella Nunez-Smith, Linda Niccolai, Albert I. Ko, J. Lucian Davis. Redesigning COVID-19 Contact Tracing for Impact and Equity.

6.1 Synthesis of findings

As we move forward into the next phase of the COVID-19 pandemic, nations around the globe will continue to grapple with weakened and stressed healthcare systems; limited access to vaccines in many areas, coupled with widespread vaccine hesitancy; evolution of SARS-CoV-2 into potentially more transmissible and/or more deadly variants; economic hardships; misinformation; and health disparities. In the face of these challenges, it is imperative that we put the lessons of the past year into action. I began this dissertation by reviewing several features of the initial phase of the COVID-19 pandemic with a particular focus on traditional contact tracing and its early implementation in the era of COVID-19. Throughout the subsequent chapters, I presented findings from a multiple and mixed methods evaluations of an emergency contact tracing program (Chapters 2-4) and a pilot evaluation of several Bluetooth-assisted contact tracing approaches (Chapter 5). I will now conclude by reviewing the major findings from each chapter and discussing the ways in which they have been applied locally and may be applied elsewhere in the COVID-19 pandemic response and beyond.

In Chapter 2, I presented a quantitative evaluation of contact tracing implementation in an emergency context. As one of the first implementation evaluations to identify and measure the reasons for case and contact drop-out and to evaluate case-, contact- and program-level factors associated with success, this work contributes novel content to the expanding literature on COVID-19 contact tracing. One of our key findings was that age and race/ethnicity were individual-level factors associated with successful outreach attempts, findings which can be used to advocate for increased community outreach among hard-to-reach populations. We also identified characteristics of ties between cases and contacts, some measured and some unmeasured, that further influenced outreach success. In particular, the associations between household and relationship status of contacts in reference to the index case and the correlated outcomes of contacts from the same case-clusters are novel findings. These identify a need to better understand how dyadic and network relationships impact contact tracing outcomes and how such ties may be harnessed to increase reach. Last, we found that adequate staffing levels were associated with successful outreach to contacts, but maintaining consistent involvement of emergency volunteers over time posed a challenge.

In Chapter 3, I presented a thematic analysis of focus groups with contact tracing volunteers whose experiences provided a wealth of insight into the context of contact tracing implementation. This remains one of the only studies to draw on the direct experience of contact tracers, and its use of qualitative data collection and analysis provides a close-up lens that is often unobtainable using quantitative methods. Using a structured implementation science framework, we identified potential strategies to increase success of outreach attempts, including identifying outreach preferences early, such as at the time-of-testing for cases, and engaging clients in a personable manner to establish trust and address concerns. We also identified many potential threats to the effectiveness of isolation/quarantine including delays in reaching cases/contacts and additional barriers related to their social, nutritional, housing, and financial needs. Regarding implementation and practice of day-to-day tasks, volunteers identified the importance of flexible data management tools, specialized protocols for the variety of encounters experienced during contact tracing, and coordination with external healthcare agencies to avoid communication burnout and confusion among cases and contacts. Last, participants provided insights into the difficulties of program adoption and maintenance, emphasizing the importance of standardized training, intra-program communication, and emotional support of staff or volunteers.

In Chapter 4, I presented a second qualitative study drawing on the direct experiences of COVID-19 cases and contacts with testing and tracing. Similar to Chapter 3, this is one of very few studies capturing the words and perspectives of those directly affected by COVID-19. Given the limited community engagement with testing and tracing, the experiences of these participants provide valuable insight into factors that influence testing and tracing behaviors. These analyses identified many ways in which physical symptoms and knowledge influence the capability of cases and contacts to engage in testing or tracing. Participants also revealed the significance of environmental resources and social ties and how such contextual factors often influenced their opportunity to engage with testing and tracing. Last, we found various ways in which motivation to participate in testing or tracing was influenced by the anticipated consequences of engagement, emotional responses to various stimuli, and trust with healthcare providers and public health programs. Identifying and characterizing these factors allowed us to propose several strategies that may increase engagement with testing and tracing.

One critical benefit of combining quantitative and qualitative methods and engaging different stakeholders is the ability to triangulate findings from Chapters 2-4. For example, both Chapter 2 and Chapter 3 identify challenges associated with delays (in data sharing and client outreach) and program sustainability. Additionally, the communications between cases and contacts described in Chapter 4 provides additional insight into the unmeasured dyadic and network characteristics identified as significant in Chapter 2. Another benefit of using both quantitative and qualitative methods is that the limitations of each chapter are, to some extent, softened by the others. For example, in Chapter 2, I was unable to evaluate isolation and quarantine outcomes due to having no quantitative data on adherence or effectiveness. However, both Chapters 3 and 4 were able to provide qualitative insights into the barriers and facilitators of isolation and quarantine.

Moving beyond the evaluation of traditional contact tracing, in Chapter 5 I presented a formative pilot study evaluating two Bluetooth technologies developed at Yale University. The development and evaluation of these technologies addressed an immediate need early on in the pandemic to better understand the potential impact that such technologies could offer as well as the feasibility and acceptability of their use. Of the two technologies evaluated, we found that the portable "tag" device had superior sensitivity and specificity. It was described by participants as easy to carry in contrast to carrying the additional study phone (used for the "app" evaluation). While one might argue that installing a Bluetooth tracing app on a personal device would eliminate the need to carry a secondary phone strictly for contact tracing, the majority of participants expressed preferences against downloading apps on personal devices. Additional preferences from participants suggested that Bluetooth was considered more appropriate than GPS/Wi-Fi modalities for contact tracing, and that university-owned/managed contact tracing platforms were perceived as more appropriate than third-party apps.

6.2 Immediate and Future Applications

Perhaps the most gratifying aspect of the work included in this dissertation was the immediate application of its findings within several local contexts. For instance, many findings from the focus groups conducted with volunteer contact tracers prompted immediate changes to protocols, internal communication strategies, and interview scripts used by the City of New Haven's contact tracing program. Furthermore, undergoing the quantitative evaluation helped our research team develop a framework for measuring key contact tracing metrics which was immediately applicable when we began supporting the Connecticut Department of Public Health's contact tracing program. As a final example, the work presented in Chapter 5 helped lead to a larger implementation pilot of the Bluetooth "tag" technology within two Connecticut high schools.

In addition to its influence on local practices, the suggestions made within this dissertation may also be applied more broadly within the COVID-19 pandemic and guide responses to future epidemics and pandemics. After reflecting on these findings and the broader context of COVID-19 contact tracing within the US and elsewhere, I identified six fundamental tactics with the potential to improve contact tracing efficiency and impact. Each of these tactics are designed to overcome one or many of the challenges faced by contact tracing in a pandemic context. Below, I describe these tactics, provide a rationale for their adoption, and review examples of their implementation in various settings. Table 6.1 presents a comprehensive list of the challenges addressed by these tactics, and examples of where such solutions have been applied (either during the COVID-19 pandemic or beforehand).

1. *Tracing and testing must be integrated rather than independent interventions.*

Current models of testing often miss opportunities to support contact tracing in several ways. First, long turnaround times for testing and reporting reduce the impact of contact tracing (1). These delays have been documented as longer for Blacks and Hispanics than for Whites (2), showing how disparities in testing subsequently lead to disparities in tracing. Reliance on outdated reporting technologies, such as fax machines and manual data entry (3), further extends such delays. Second, and as clearly demonstrated in Chapter 2, test results are occasionally reported without accurate phone numbers or clients' language preference, preventing outreach to COVID-19 cases and their contacts. Furthermore, the time-of-testing is overlooked as an opportunity to encourage cases to participate in subsequent contact tracing activities. Delaware's experience in the first year of the pandemic was typical of many states, in that tracers were unable to reach over one-third of all cases and two-thirds of all reported contacts (4). Missing telephone numbers accounted for nearly half of these losses, with the remainder attributable to repeatedly unanswered calls or refusals to be interviewed. An additional 20% of cases, when interviewed, reported no contacts at all, and at the end of the tracing process, a mere 6%

of contacts ever received coronavirus testing. One final example of the failure to integrate testing and tracing is the absence of screening or referral services for social support needs at most testing sites. It is evident from Chapters 3 and 4 that such social needs are critical to isolation and quarantine adherence, and the time-of-testing provides an opportunity to identify and respond to these needs more rapidly.

Because a primary purpose of SARS-CoV2 testing should be to guide interventions to prevent onward spread, testing must be redesigned to prioritize this objective. First, rapid on-site testing, even if modestly less sensitive, would speed up initiation of tracing, as would direct digital case-reporting into contact tracing databases. Second, the testing visit should be used to collect and validate outreach information, convey expectations about contact tracing follow-up, and link cases to needed social support services. Such strategies could learn from best practices in tuberculosis care, in which contact tracing is often introduced at the time of testing, diagnosis, or treatment initiation, rather than deferred to a subsequent and unsolicited call from a stranger. To further increase participation in contact tracing and isolation, messaging at testing sites could employ "nudge" framing. For example, prosocial messages might emphasize how tracing benefits the community, since such appeals may inspire greater participation than appeals that emphasize benefits to the individual (5). Similarly, normative messaging that presents contact tracing as the default choice, as well as messaging that recasts cases as role models rather than as victims, could further motivate participation. Third, contact testing when indicated should be encouraged and supported by making testing free, arranging transportation to test sites, and facilitating home- or community-based testing (6) when possible, as supported by the findings in Chapter 4. As one of the largest payors for testing, the federal government is well-positioned to incentivize or mandate testing models that support tracing and maximize reach and timeliness. It is appropriate that communities realize a public health return on these federal investments.

2. *Tracing teams that bridge multiple health jurisdictions and partner with local health departments are needed to maximize flexibility and impact.*

Hiring and retaining sufficient numbers of tracers to match shifting caseloads has posed a major challenge to scaling contact tracing for COVID-19, as discussed in Chapter 2. Another challenge has been training tracers in interviewing and counseling techniques so that they can effectively elicit the necessary information to trace contacts, while supporting those individuals who may be suffering or grieving, as described in Chapters 3-4. Although paid workforces are more sustainable over time, early staffing experiments with volunteers helped identify desirable attributes of an effective contact tracing workforce. Assembling teams of diverse age, gender, and language competencies and offering flexible work hours are important to a program's ability to reach more cases and contacts at the right time and with the right tone.

Several states (7), including New York and Massachusetts, have applied these lessons in establishing virtual call centers. Dedicated staff quickly achieve competency and efficiency through standardized training and practice. Adaptable staffing models allow reallocation of workers to jurisdictions where they are most needed during surges.

Centralizing the responsibility for initial outreach in call centers also benefits local health department officials by freeing them to focus on local activities. For example, they are better positioned to provide customized follow-up, support, and monitoring for the hard-to-reach and the vulnerable and to coordinate with community-based organizations as described further below. A hybrid model in which call center staff work consistently with specific local health departments has enabled Washington State to reach 80% of contacts within two days of a positive case report (8) and provide personalized community support when needed.

3. *Contact tracing strategies must be adaptable to caseloads and incidence.*

Fluctuating caseloads and rapidly evolving scientific knowledge about COVID-19 have left contact tracing programs constantly adapting to meet community needs with the recommended best practices. When incidence levels are high, programs often lack the resources to reach all cases and contacts efficiently. At the same time, they may also lack prioritization strategies that could guide a more focused approach to first reaching those who are most likely to benefit. On the other hand, when incidence levels are low, resources are often redirected away from tracing programs, not allowing them to pursue more comprehensive or creative approaches to tracing. As caseloads inevitably ebb and surge, programs must be able to reallocate resources to maximize equity and impact.

When incidence surges, programs should prioritize contacting cases based on their risk for community spread, morbidity, and mortality (9). Such prioritization strategies are especially important considering the Chapter 1 findings that elderly, at-risk cases were less likely to be reached. Factors such as time since symptom onset, sputum viral load, SARS-CoV-2 variant type, and number and comorbidities of contacts might also be productively used to maximize the impact and equity of outreach efforts. When incidence falls, programs may then free up capacity to expand contact tracing to accelerate containment efforts. For example, in addition to “forward tracing” to identify contacts, programs may adopt “backward tracing” to identify missed sources and chains of transmission, as done in Japan (10), or extend tracing and quarantine to second- and third-order contacts, as done in Vietnam (11).

4. *There is a need to embrace new technologies to improve the efficiency of tracing.*

Although the United States leads the world in developing information technology, efforts to apply digital solutions to the public health response to COVID have been limited and ineffective. For example, only a limited proportion of the U.S. population has signed up for any of the public, Bluetooth-enabled, contact tracing apps (7). Such low uptake is likely due in part to privacy concerns and a lack of effective messaging about its benefits to the community, as supported by the participant concerns identified in Chapter 5. To increase acceptance of Bluetooth and other proximity-based contact tracing apps, we must clearly communicate how individual data are protected and explore incentives to increase participation. Blockchain technology (12) may increase the security of tracing apps, while incentives such as monetary rewards for app installation, as demonstrated in Germany (13), or allowing access to indoor dining or retail locations only to app users may increase adoption. In private work, school, or health settings, wearable tracing technologies, such as Bluetooth or radio-frequency tags or badges, may also be more feasible, acceptable and accurate (14).

We must also consider other technologies to improve efficiency. First, testing and tracing programs could introduce secure, case-facing data-entry interfaces for online and mobile platforms, as Rhode Island (15) has done. These portals allow cases to securely report contacts and outreach information at the time-of-testing, allowing the community to "trace itself" when able. Second, similar online or SMS-based messaging services could be expanded to allow clients to access informational materials, request support for isolation and quarantine, and receive automated monitoring (16). Variations in literacy and comfort with information technology may potentially worsen disparities in access and uptake of such interventions, but these approaches would reduce the overall workload for contact tracing staff, affording them more time to serve those in need of person-to-person services. Furthermore, such approaches may increase feasibility of participation for cases unable to conduct phone calls due to respiratory symptoms, as discussed in Chapter 4.

5. *Reporting of tracing outcomes must be standardized and transparent to improve equity and impact.*

To date, many states still do not report contact tracing metrics publicly, and the existing dashboards vary greatly in how they report data and outcomes. For example, few dashboards include information about timeliness, equity of outcomes by race, ethnicity, and geography, or proportions of cases and contacts receiving support for isolation and quarantine. Missing individual-level data on race and ethnicity and other factors that may inform tailoring of contact tracing to individual needs is a principal barrier to reducing inequities. As we developed our program evaluation framework, the amount of variability in reporting of contact tracing outcomes across US states was astonishing. To improve the implementation of contact tracing, we must increase the quality of our data collection and reporting in several ways.

First, increasing transparency by incentivizing public reporting and proposing standardized indicators would better enable comparisons, and, in turn, identification and dissemination of best practices. Second, data capture must be optimized to provide population-stratified data on the yield and timeliness of contact tracing. These metrics should be publicly reported alongside test positivity and case-incidence metrics to better promote equity and accountability. When data are missing, there should be greater efforts to cross-link tracing databases with existing health information (17). Alternatively, combined geography- and surname-driven prediction methods [e.g., Bayesian Improved Surname Geocoding (18)] and ecologic analyses informed by census tract data may be used.

6. *Support for individuals and communities during isolation and quarantine is critical to equity and impact.*

No matter how well programs do with outreach, the benefits of contact tracing will be lost without effective isolation and quarantine, as clearly demonstrated in Chapters 3 and 4. Programs must address factors that influence adherence to isolation or quarantine, including trust in health systems, employment concerns, caregiving duties, and community norms (19). They must do so proactively through community-wide messaging to establish norms and strive to identify individual case or contact needs at an early stage as discussed above. Programs must also be vigilant about the many ways that inequities affect the ability to isolate or quarantine and seek to actively support the disadvantaged (20). For example, Chapter 4 highlighted the difficulties experienced by non-English speakers, caregivers, and those without health insurance. Expanding partnerships with community-based organizations and employing outreach workers from unreached communities, as done in Chicago (21), are two strategies to help achieve this end. Such collaborations can also inform redesign of processes and messaging to improve impact. Other possible solutions to encourage and enable isolation, quarantine, and testing include direct and digital social marketing, paid sick leave and employment protections, and home delivery of self-testing kits, food, and other essential supplies.

6.3 Conclusions

To conclude, the tactics outlined above all aim to improve contact tracing implementation outcomes, although each tactic may be more or less feasible in different scenarios depending on local resource limitations and context. However, the examples provided of each tactic in practice demonstrate that such strategies are indeed feasible under the right circumstances. In light of the impressive difficulties encountered during the implementation of contact tracing for COVID-19, one may reasonably ask whether it is truly worth the resources, time, and commitment it would take to revise our approach and improve.

On one hand, modelling studies have predicted little to no impact on disease transmission when benchmarks for yield and timeliness are not met. To this point, I would refer to the tracing programs cited throughout this dissertation that have reached, or have nearly reached, the efficiency benchmarks set forth by the CDC, providing reasonable hope that such accomplishments are achievable. The other cited studies reporting associations between contact tracing and reduced COVID-19 incidence and case fatality further emphasize the potential benefits of this intervention, and future research will hopefully shed more light on how the strength of this association is modified by the efficiency of contact tracing. One might also argue that stricter social distancing measures, such as lockdowns, may contribute more to transmission reduction than contact tracing, especially during case surges. While a reasonable argument, lockdowns are a temporary solution, whereas contact tracing offers a more sustainable alternative that may continue even after such lockdowns end. Furthermore, the scope of contact tracing goes beyond reducing transmission by also providing a range of medical and social services to cases and contacts. Comprehensive and client-centered approaches to contact tracing strive to monitor and link clients to medical care when needed, support clients through isolation and quarantine via provision of financial, nutritional, and other social resources, and establish community trust through demonstrated care. Such benefits of contact tracing exist even when benchmarks for yield and timeliness are not met. Finally, one might argue that other pandemic interventions, namely vaccination, must be prioritized above contact tracing. To this point, I would argue that contact tracing and vaccination need not be considered competing interventions. Transmission will remain largely concentrated in unvaccinated populations, and contact tracing therefore provides an opportunity to engage with unvaccinated cases and contacts to encourage and support linkage to vaccination. Additionally, even in regions with high vaccination rates, breakthrough transmission remains a risk, and contact tracing will be needed to respond to these events. In sum, despite the challenges faced by COVID-19 contact tracing, we must strive to set aside defeatism and take action to improve implementation. Locally and beyond, the findings identified herein aim to support this process.

Table 6.1: Challenges to contact tracing, associated barriers, and proposed solutions, with examples and supporting evidence

Challenges	**Barriers**	**Proposed solutions**	**Examples and supporting evidence from COVID and non-COVID contexts**
Testing is not currently designed to support tracing.	Slow testing turnaround-time delays initiation of tracing.	Prioritize rapid, point-of-care testing.	Rapid testing for COVID-19 (22, 23)
	Slow reporting delays initiation of tracing.	Replace fax and other outdated reporting systems with digital reporting to tracing databases.	Taiwan's Laboratory Automated Reporting System (LARS) (24, 25)
	Not collecting phone numbers and outreach preferences at the time of sample collection reduces the yield of tracing.	Use the time of sample collection or results delivery to collect and validate outreach preferences for contact tracing.	TB guidelines (26) recommend (a) collecting accurate case data prior to interview and (b) conducting initial outreach in-person at the clinic, hospital, or home as soon as possible after results reporting.
	Not engaging and educating cases at the time of sample collection reduces both the yield of tracing and adherence to isolation and quarantine.	Use the sample collection visit to engage and educate cases using prosocial messaging and normalization strategies.	Pro-social messaging campaigns for COVID-19 (5)
	Barriers and disincentives to testing (costs of testing, prolongation of quarantine/isolation period) reduce testing rates among contacts.	Incentivize and support testing for contacts by making testing free, arranging transportation, and pursuing in-home or community testing when possible, and by providing immunity passports to those with confirmed prior cured infections to allow safe access to public venues pending timely vaccination.	Community-based COVID-19 testing (27) Immunity passports (28)
Contact tracing programs have struggled to staff and train large workforces.	Fluctuating caseloads make finding, training, and retaining sufficient numbers of tracers difficult and expensive.	Centralize contact tracers within State health departments, where increased funding facilitates hiring of sufficient staff, and human resources may be allocated across jurisdictions to match changes in caseloads.	Centralization of contact tracing staff in several US states (29)
	Contact tracing requires multiple tasks, ranging from delivery of test results to contact	Delegate standard case and contact interviews to centralized call center staff in order to free local health	Partnerships between several US state health departments and local officials or community

	elicitation to arranging support with isolation and quarantine.	departments and community organizations for personalized follow-up and support.	organizations for personalized follow-up and linkage to social supports (29, 30)
The feasibility and impact of contact tracing decrease as incidence rises and increase as incidence falls.	When case incidence is high, health departments may lack sufficient staff to reach all cases and all contacts in a timely manner.	When case incidence is high, focus on core contact tracing objectives by prioritizing outreach based on potential for community spread, morbidity, and mortality using risk factors including time since symptom onset, viral load, comorbidities, age, and number of contacts.	CDC's prioritization strategies (9)
	When case incidence is low, health departments often lack training and experience employing intensified tracing approaches that could increase the impact of contact tracing.	When case incidence is low, expand tracing techniques to include backward tracing and outreach to second- and third-order contacts.	Backward contact tracing (10) Second- and third-order contact tracing (11)
COVID-19 contact tracing is too time-consuming and too labor-intensive.	Widespread concerns about data privacy limit participation in Bluetooth contact tracing.	Clearly communicate how individual data is protected and explore incentivization strategies to increase participation (such as allowing increased access to indoor dining or retail locations).	Acceptability of smartphone apps for contact tracing (31, 32) Blockchain technology for tracing (12) Small, monetary incentives to increase app uptake (13) Wearable digital contact tracing devices (14)
	Missed opportunities to automate data collection from verifiable case-facing data entry forms.	Provide secure case-facing data entry forms to allow cases to report contacts or identify support needs either at the time-of-testing or packaged with test results.	Rhode Island's COVID-19 "Results Portal" (15)
	Missed opportunities to automate monitoring and delivery of educational resources to cases and contacts during isolation and quarantine.	Use automated online or SMS-based strategies to lighten demands on human tracers and reallocate their time to activities or populations in need of human tracers.	Maine's use of automated monitoring for COVID-19 contacts (16)
A lack of data on contact tracing performance is a major barrier to improving equity and quality.	Lack of transparency in data reporting makes it difficult to assess the overall impact of contact tracing around the country.	Mandate or incentivize data reporting while providing standardized metrics for evaluating efficiency and effectiveness.	Exemplary Contact Tracing Dashboards: • Delaware (4) • Massachusetts (33) • New Jersey (34) • Washington (8)
	Missing individual-level data on race	Link contact tracing databases with external	Taiwan's linkage of health databases (17)

	ethnicity restrict our ability to identify and respond to inequity.	health databases; train contact tracers to ensure competency and confidence in collecting demographic information from cases.	Bayesian Improved Surname Geocoding (BISG) to predict missing race data based on name and census tract (18)
Many individuals are physically or financially unable to isolate or quarantine.	Many cannot meet their responsibilities to feed, financially support, and care for household members who need assistance, among other obligations.	Provide food and care packages; mediate work leave; provide paid sick leave	Support strategies for self-isolation (and quarantine) (20)
	Needs are not identified and addressed at diagnosis, when needs are greatest, and patients are most infectious.	Individual needs must be assessed as early as possible, either at sample collection or upon delivery of results for cases, and during initial outreach to contacts.	Test-to-Care model implemented in San Francisco (6)
	Individuals from vulnerable communities may distrust advice from government and public health.	Local partnerships and hiring of outreach workers from vulnerable communities; Increased funding directed towards vulnerable communities.	Chicago's community-based contact tracing corps (21)

6.3 References

1. Ferretti L, Wymant C, Kendall M, Zhao L, Nurtay A, Abeler-Dorner L, et al. Quantifying SARS-CoV-2 transmission suggests epidemic control with digital contact tracing. Science. 2020;368(6491).
2. Chwe H, Quintana A, Lazer D, Baum MA, Perlis RH, Ognyanova K, et al. The COVID States Project Report #17: COVID-19 TEST RESULT TIMES 2020 [March 30, 2021]. Available from: https://osf.io/rz34x/.
3. Kliff S, Sanger-Katz M. Bottleneck for U.S. Coronavirus Response: The Fax Machine 2020 [March 30, 2021]. Available from: https://www.nytimes.com/2020/07/13/upshot/coronavirus-response-fax-machines.html.
4. State of Delaware: Coronavirus (COVID-19) Data Dashboard 2021 [March 29, 2021]. Available from: https://myhealthycommunity.dhss.delaware.gov/locations/state/coronavirus-mitigation#contact_tracing.
5. Yoeli E, Rand D. A checklist for prosocial messaging campaigns such as COVID-19 prevention appeals PsyArXiv Preprints. 2020.
6. Kerkhoff AD, Sachdev D, Mizany S, Rojas S, Gandhi M, Peng J, et al. Evaluation of a novel community-based COVID-19 'Test-to-Care' model for low-income populations. PLoS One. 2020;15(10):e0239400.
7. State Approaches to Contact Tracing during the COVID-19 Pandemic 2021 [March 30, 2021]. Available from: https://www.nashp.org/state-approaches-to-contact-tracing-covid-19/#tab-id-3.
8. Case Investigation and Contact Tracing Metrics for DOH Centralized Investigations 2021 [March 30, 2021]. Available from: https://www.doh.wa.gov/Emergencies/COVID19/DataDashboard.
9. Prioritizing Case Investigations and Contact Tracing for COVID-19 in High Burden Jurisdictions 2021 [March 30, 2021]. Available from: https://www.cdc.gov/coronavirus/2019-ncov/php/contact-tracing/contact-tracing-plan/prioritization.html.
10. Endo A, Centre for the Mathematical Modelling of Infectious Diseases C-WG, Leclerc QJ, Knight GM, Medley GF, Atkins KE, et al. Implication of backward contact tracing in the presence of overdispersed transmission in COVID-19 outbreaks. Wellcome Open Res. 2020;5:239.
11. Lewis D. Why many countries failed at COVID contact-tracing — but some got it right. Nature. 2020.
12. Idrees SM, Nowostawski M, Jameel R. Blockchain-Based Digital Contact Tracing Apps for COVID-19 Pandemic Management: Issues, Challenges, Solutions, and Future Directions. JMIR Med Inform. 2021;9(2):e25245.
13. Munzert S, Selb P, Gohdes A, Stoetzer LF, Lowe W. Tracking and promoting the usage of a COVID-19 contact tracing app. Nat Hum Behav. 2021;5(2):247-55.
14. Huang Z, Guo H, Lee YM, Ho EC, Ang H, Chow A. Performance of Digital Contact Tracing Tools for COVID-19 Response in Singapore: Cross-Sectional Study. JMIR Mhealth Uhealth. 2020;8(10):e23148.
15. COVID-19 Contact Tracing 2021 [March 30, 2021]. Available from: https://covid.ri.gov/covid-19-prevention/contact-tracing.

16. Krueger A, Gunn JKL, Watson J, Smith AE, Lincoln R, Huston SL, et al. Characteristics and Outcomes of Contacts of COVID-19 Patients Monitored Using an Automated Symptom Monitoring Tool - Maine, May-June 2020. MMWR Morb Mortal Wkly Rep. 2020;69(31):1026-30.
17. Lin C, Braund WE, Auerbach J, Chou JH, Teng JH, Tu P, et al. Policy Decisions and Use of Information Technology to Fight COVID-19, Taiwan. Emerg Infect Dis. 2020;26(7):1506-12.
18. Adjaye-Gbewonyo D, Bednarczyk RA, Davis RL, Omer SB. Using the Bayesian Improved Surname Geocoding Method (BISG) to create a working classification of race and ethnicity in a diverse managed care population: a validation study. Health Serv Res. 2014;49(1):268-83.
19. Webster RK, Brooks SK, Smith LE, Woodland L, Wessely S, Rubin GJ. How to improve adherence with quarantine: rapid review of the evidence. Public Health. 2020;182:163-9.
20. Cevik M, Baral SD, Crozier A, Cassell JA. Support for self-isolation is critical in covid-19 response. BMJ. 2021;372:n224.
21. Community-Based Organizations Selected to Create Contact Tracing Corps 2020 [March 30, 2021]. Available from: https://publichealth.uic.edu/news-stories/community-based-organizations-selected-to-create-contact-tracing-corps/.
22. Crozier A, Rajan S, Buchan I, McKee M. Put to the test: use of rapid testing technologies for covid-19. BMJ. 2021;372:n208.
23. Mina MJ, Parker R, Larremore DB. Rethinking Covid-19 Test Sensitivity - A Strategy for Containment. N Engl J Med. 2020;383(22):e120.
24. Jian SW, Chen CM, Lee CY, Liu DP. Real-Time Surveillance of Infectious Diseases: Taiwan's Experience. Health Secur. 2017;15(2):144-53.
25. Jian SW, Cheng HY, Huang XT, Liu DP. Contact tracing with digital assistance in Taiwan's COVID-19 outbreak response. Int J Infect Dis. 2020;101:348-52.
26. Centers for Disease Control and Prevention. Guidelines for the investigation of contacts of persons with infectious tuberculosis; recommendations from the National Tuberculosis Controllers Association and CDC. MMWR Recomm Rep. 2005;54(RR-15):1-47.
27. Kim HN, Lan KF, Nkyekyer E, Neme S, Pierre-Louis M, Chew L, et al. Assessment of Disparities in COVID-19 Testing and Infection Across Language Groups in Seattle, Washington. JAMA Netw Open. 2020;3(9):e2021213.
28. Persad G, Emanuel EJ. The Ethics of COVID-19 Immunity-Based Licenses ("Immunity Passports"). JAMA. 2020;323(22):2241-2.
29. State Approaches to Contact Tracing during the COVID-19 Pandemic 2021 [March 29, 2021]. Available from: https://www.nashp.org/state-approaches-to-contact-tracing-covid-19/.
30. Care Connect Washington 2021 [March 30, 2021]. Available from: https://www.doh.wa.gov/Emergencies/COVID19/CareConnectWashington.
31. Garrett PM, White JP, Lewandowsky S, Kashima Y, Perfors A, Little DR, et al. The acceptability and uptake of smartphone tracking for COVID-19 in Australia. PLoS One. 2021;16(1):e0244827.

32. Altmann S, Milsom L, Zillessen H, Blasone R, Gerdon F, Bach R, et al. Acceptability of App-Based Contact Tracing for COVID-19: Cross-Country Survey Study. JMIR Mhealth Uhealth. 2020;8(8):e19857.
33. Massachusetts COVID-19 Response Reporting 2021 [March 30, 2021]. Available from: https://www.mass.gov/info-details/covid-19-response-reporting#covid-19-interactive-data-dashboard-.
34. New Jersey COVID-19 Dashboard 2021 [March 29, 2021]. Available from: https://www.nj.gov/health/cd/topics/covid2019_dashboard.shtml.