smw • swiss medical weekly

Original article | Published 22 October 2023 | doi:https://doi.org/10.57187/smw.2023.40112
Cite this as: Swiss Med Wkly. 2023;153:40112

Contact tracing for COVID-19 in a Swiss canton: analysis of key performance indicators

Leonie Heron[a], Catrina Mugglin[a], Kathrin Zürcher[a], Erich Brumann[b], Bettina Keune-Dübi[b], Nicola Low[a], Lukas Fenner[a]

[a] Institute of Social and Preventive Medicine, University of Bern, Bern, Switzerland
[b] Cantonal Physician's Office, Canton of Solothurn, Solothurn, Switzerland

Summary

BACKGROUND: Contact tracing (CT) has played an important role in strategies to control COVID-19. However, there is limited evidence on the performance of digital tools for CT and no consensus on which indicators to use to monitor their performance. We aimed to describe the system and analyse outcomes of CT with a partially automated workflow in the Swiss canton of Solothurn, using key performance indicators (KPIs).

METHODS: We describe the process of CT used in the canton of Solothurn between November 2020 and February 2022, including forward and backward CT. We developed 16 KPIs representing CT structure (S1–2), process (P1–11) and outcome (O1–3) based on previous literature to analyse the relative performance of CT. We report the changes in the indicators over waves of SARS-CoV-2 infections caused by several viral variants.

RESULTS: The CT team in Solothurn processed 57,363 index cases and 71,809 contacts over a 15-month period. The CT team successfully contacted 99% of positive cases within 24 hours (KPI P7) throughout the pandemic and returned almost all test results on the same or next day (KPI P6), before the delta variant emerged. Three-quarters of contacts were notified within 24 hours of the CT interview with the index (KPI P8) before the emergence of the alpha, delta and omicron variants, when the proportions decreased to 64%, 36% and 54%, respectively. The percentage of new symptomatic cases tested and interviewed within 3 days of symptom onset was high at >70% (KPI P10) and contacts started quarantine within a median of 3 days of index case symptom onset (KPI P3). About a fifth of new index cases had already been in quarantine by the time of their positive test (KPI O1), before the delta variant emerged. The percentage of index cases in isolation by day of testing remained at almost 100% throughout the period of analysis (KPI O2).

CONCLUSIONS: The CT in Solothurn used a partially automated workflow and continued to perform well throughout the pandemic, although the relative performance of the CT system declined at higher caseloads. CT remains an important tool for controlling the spread of infectious diseases, but clearer standards should improve the performance, comparability and monitoring of infection in real time as part of pandemic preparedness efforts.

Prof. Lukas Fenner
Institute of Social and Preventive Medicine
University of Bern
Mittelstrasse 43
CH-3012 Bern
lukas.fenner[at]unibe.ch
and
Dr Bettina Keune-Dübi
Kantonsärztlicher Dienst
Gesundheitsamt Kanton Soloturn
Riedholzpl. 3
CH-4509 Solothurn
bettina.keune[at]ddi.so.ch

Introduction

Contact tracing (CT) has been an important part of strategies to reduce the spread of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) infections and control the coronavirus disease 2019 (COVID-19) pandemic [1–2]. Forward CT involves identifying contact persons whom the index case might have infected, whereas backward CT involves finding the source of the infection of the index case. Backward tracing appears to be more effective for controlling COVID-19, based on the principle that the person who infected the index is likely to have had more contacts than the index themself [3–4]. In Japan, public health experts have suggested that forward CT is only feasible below a 7-day incidence threshold of 15 cases per 100,000 people (Hitoshi Oshitani, personal communication, 7 February 2022). The 'test-trace-isolate-quarantine' strategy, which includes CT activities, can break chains of transmission [5]. During the COVID-19 pandemic, authorities were under pressure to quickly establish CT systems and deal with surges in cases. Although public health authorities quickly trained individuals to join CT teams [6], there was a great need to incorporate a variety of digital tools into CT systems to reduce the high workload of tracers and make CT more efficient [7].

There is limited evidence on the performance of digital outbreak response tools [8]. According to the World Health Organization (WHO), outbreak response tools [9] are workflows that facilitate data entry and automated communication with cases and contacts, particularly when caseloads are high. They are also known as partly automated CT systems [8] as some parts of the system are automated, e.g. messages are sent automatically, whereas other tasks need to be done by a human, e.g. the index case providing contact details in an online form or an in-person interview. These digital systems are distinct from proximity tracing applications [10], which are used as complementary tools to notify users that they have been in close physical proximity to an infected person [9].

Several key performance indicators (KPIs) have been used to evaluate the performance of CT for COVID-19 [11–12] and can be categorised according to whether they measure the structure, process or outcome of a public health intervention like CT [13]. According to Swiss law, the cantonal physician's office in Solothurn was responsible for implementing CT and they developed a partially automated CT workflow in their canton, which was introduced after the first wave of the COVID-19 pandemic. The objectives of the present study were 1) to describe the CT system developed by the Swiss canton of Solothurn and 2) to describe KPIs to analyse CT outcomes between the implementation of new CT software on 15 November 2020 (onset of the second wave) and 2 February 2022, at which point the Federal Office of Public Health (FOPH) of Switzerland ended the requirement to isolate [14].

Methods

We used CT data that were routinely collected between 15 November 2020 and 2 February 2022. More details about the canton of Solothurn, definitions and CT practices can be found in supplementary file 1 and in a previous analysis [15]. We did not prepare a statistical analysis plan in advance.

Context

Solothurn is a mid-sized canton in Switzerland with a population of approximately 280,000 [16]. The official language is German and three quarters (213,800; 76%) of the population are Swiss, which is similar to Switzerland as a whole (supplementary table 1). Over the course of the COVID-19 pandemic, the Swiss government and the canton of Solothurn imposed several measures to reduce transmission of SARS-CoV-2 including restrictions on gatherings, mask mandates, school closures, travel quarantines, but also the provision of contact data based on the Epidemics Act law and FOPH directives [14, 17]. As of December 2022, 139,717 SARS-CoV-2 infections had been confirmed in Solothurn and 379 people reported to have died of COVID-19 [18]. The epidemiological landscape has changed with the emergence of new SARS-CoV-2 variants of concern (VOC) [19], and population immunity through infection and vaccines, licensed in Switzerland since December 2020.

Contact tracing practices and data collection system

Definitions

We defined an index case as an individual who tested positive for SARS-CoV-2 by a polymerase chain reaction (PCR) test or a positive rapid antigen test after their introduction at the end of 2020 within the testing criteria (adult within four days of symptom onset, non-healthcare worker, non-vulnerable person) with legal residency in the Swiss canton of Solothurn. Index cases were required to isolate for 10 days either from the date of the positive test result or the date of symptom onset. Close contacts were defined as Solothurn residents who had either spent at least 15 minutes with an index case at a distance of less than 1.5 metres without wearing a face mask or were living in the same household as the index case in the two days before testing positive [14].

Contact tracing practices and digital workflow

The CT team collected data from index cases and contacts through in-depth telephone interviews and the collation of self-reported information from online forms. After the first epidemic wave in spring 2020, the public health authorities of the canton of Solothurn implemented a process-oriented CT software “Straatos” at the beginning of the second epidemic wave in October 2020 [20–21] (see supplementary file 1 for details). Index cases received a link via text message to an online form after testing positive (supplementary files 1 and 2). Index cases reported their age, sex, place of residence, symptoms, date of symptom onset, potential source of infection, vaccination status, close contacts, and places visited before symptom onset or positive test if asymptomatic. The CT system then automatically emailed the index case an ‘administrative order’, digitally signed by the cantonal physician, which ordered the individual to isolate, based on the Epidemics Act [17]. The CT staff telephoned index cases within one day of their positive test result to confirm their responses to the online form, whenever workload allowed it (see contingency planning in supplementary file 3). Afterwards, the contact tracer would discuss the information provided with another member of staff. The index cases received an automated text message at the end of isolation on day ten (to 12 January 2022) or on day five (from 13 January 2022) to report any symptoms online. There was a three-step ‘traffic light’ system with levels one (indicating a low caseload and high staff availability) to four (indicating high caseload and low staff availability) to determine the extent to which staff would individually contact the index cases and contacts, check vaccination documents and test orders, and implement CT in institutional and business settings (supplementary file 3). The levels were not objectively defined; usually, the level increased at the beginning of a wave of infection. For example, at levels one and two, the CT staff contacted the index cases on days six and ten. However, at level three they only contacted them on these days when there were sufficient resources and at level four they did not contact them on these days.

Close contacts identified through forward CT received a text message with a link to an online form (supplementary file 2). The text of the message instructed them to quarantine at home and get tested five days after their last contact with the index case. Contacts reported their age, sex, vaccination status, workplace or school, and email address. Contacts were also emailed an ‘administrative order’ [17], which included information on what to do if they developed symptoms, current recommendations by the FOPH, links to the FOPH website, and a telephone number and email address if they needed more information. The contacts were called by telephone in the first two days of quarantine and at the end of the quarantine, depending on the caseload. Contacts received an automated text message on day five of quarantine to remind them to get tested. At the onset of the omicron wave (27 December 2021), the workload was judged to be too high to continue to call contacts at the start of the quarantine period by telephone. From January 2021, contacts could leave quarantine on day 7 if they tested negative for SARS-CoV-2. After this date, contacts were only telephoned at the end of quarantine in exceptional circumstances.

The CT team in Solothurn started backward tracing (in addition to forward tracing) on 15 November 2020. Index cases reported locations and events visited in the 10 days prior to testing positive using an online form (supplementary table 2 and file 1) and provided data were reviewed during the telephone interview. The CT software automatically identified index patients who could belong to a cluster because of attendance at the same event, bar, school, nursing home, or sharing a residential building (supplementary file 1). When staff capacity allowed, the CT team contacted the venues at which index cases had reported visiting in the ten days before infection. Based on this information, a mobile testing team (run by the two cantonal testing centres) was sent out.

Key performance indicators

We defined 16 KPIs: 2 for the structure, 11 for processes and 3 for outcomes of CT (supplementary table 3) [13]. The KPIs were based on previous research [11, 22] and an unpublished list of COVID CT indicators that had been discussed early in the pandemic [12]. 'Structure' indicators relate to the setting, including human resources and equipment in a CT context. They included quantification of the proportion of individuals using the Swiss Covid digital tracing application, used to notify individuals when they had been in close proximity to a positive case [23], and the capacity of the CT workforce over time, measured as the number of full-time equivalent (FTE) staff. "Process" indicators measured the speed and completeness of investigating, testing and CT. "Outcomes" of CT refer to measures that should indicate whether a chain of transmission could have been broken. Most (13) KPIs for COVID-19 CT had associated targets (supplementary table 3) [11–12, 22]. Index cases without a case date (date of first contact with the index case) were removed. Dates that were 25 days before or after the automatically generated case date were removed if we deemed them likely due to a typographical error.

Statistical analysis

We describe the level of engagement with CT in Solothurn at each stage in a cascade of CT processes. We also describe the characteristics of the index cases and compare them with Swiss national data (from the FOPH). We report their reported source of infection, activities or locations where they spent time in the ten days before testing positive, their number of close contacts and the characteristics of the close contacts. Several SARS-CoV-2 variants were circulating at the same time; we have indicated the dominant viral variant based on national testing data (supplementary file 1). We calculate KPIs by period of dominant viral variant and plot KPIs against the incidence rate of SARS-CoV-2 over the entire period. All analyses were conducted using R (version 3.5.1). The analysis code is available at https://github.com/leonieheron.

Ethics statement

In accordance with the Swiss Epidemics Act, informed consent is not required for the collection or processing of personal data in the context of outbreak investigations and containment of infectious diseases. We obtained approval from the Ethics Committee of Northwestern and Central Switzerland (EKNZ, reference nº 2022-00261, www.swissethics.ch) to analyse CT data and publish only anonymised data.

Results

Description of contact tracing

Over sixty thousand (n = 60,378) positive tests were recorded in the canton of Solothurn from 15 November 2020 to 2 February 2022 (figure 1). The CT team contacted almost all positive cases (95%, n = 57,363) by text message through the CT software and, if workload allowed, additionally by phone. The remaining 5% of cases came from nursing homes. Nursing home residents were called individually (via the health service of the nursing home), and these calls were documented outside of the CT system in November and December 2020. A total of 57,360 individuals (all but 3) submitted the online form. The index cases reported 71,809 contacts, all of whom were contacted by the CT team. The majority of contacts (93%, n = 66,934) submitted an online form. Only 66,261 of the 71,809 (92%) contacts reported by the index cases completed an online form. 5548 contacts were not linked to any index cases, most of them came from outside the canton (n = 4481). The other contacts (n = 1167) were either referred by the FOPH because they were on a flight with a confirmed infection aboard or the reason was unknown. Nine percent (n = 5830) of the contacts who completed the online form later tested positive themselves and became index cases.

Overall, the distribution of index cases according to age and sex was similar to that of the general population in Switzerland (table 1, supplementary table 1). The proportion of children (aged 0–17 years) in CT increased from 7% (n = 503) before the periods of VOCs to 30% and 27%, respectively, when delta and omicron were the dominant VOCs. The increasing proportion of children in CT partly reflects relaxations in COVID-19 measures in Swiss schools, which were replaced with the repeated testing of students in June 2021, and most children were not vaccinated, meaning that they were not exempt from quarantine. The symptoms most commonly reported by the index cases were cough (46%), runny nose (39%) and sore throat (34%) although the distribution of symptoms changed as new viral variants emerged (table 1). Loss of taste or smell was more common in the period before the alpha VOC emerged (23%) compared with 12% overall. In the period during which alpha was the dominant VOC, relatively more people reported no symptoms (27% compared with 18% overall). During the period when delta was the dominant VOC, more people reported a cough or a runny nose (49% and 43% compared with 46% and 39% overall). Finally, while omicron was the dominant VOC, a sore throat was relatively more common (39% compared with 34% overall).

The proportion of vaccinated individuals increased over time. By the omicron period, 48% of all index cases had been vaccinated with at least two doses. While only 0.1% (n = 65) and 1.3% (n = 737) of the age and gender data were missing, respectively, 7.1% (n = 4062) of the data on symptoms were missing. If participants did not answer the question on vaccination status, we assumed that they had not been vaccinated.

Backward contact tracing

Eleven thousand (n = 11,072, 19%) index cases reported at least one group activity in the ten days before symptom onset or positive test (table 2). Most cases (n = 46,288; 81%) did not report any activities. Of those who did, most reported only one activity (67%) although the maximum was 23. The most common activities reported in the last 10 days were being at a fitness centre or doing sports, private parties, working, or dining with others at home or in a restaurant. During the period when omicron was the dominant VOC, a much higher proportion of people did not report any information on activities. Out of the index cases who reported attending a certain location, 30% reported that they knew of a positive case who had also attended. The proportion increased as the pandemic continued: in 13% (n = 430) of venues visited and reported by index cases, the index case knew of a positive case in attendance during the pre-VOC period, 8% (n = 284) in the period during which alpha was the dominant VOC, 34% (1139) while the delta VOC was dominant, and 45% (n = 1516) while the omicron VOC was dominant. Most index cases reported their likely source of infection (91%, n = 52,350). The most common responses were family or friends (39%), school (13%), work (9%), or shopping/public transport (5%). Fourteen percent of respondents could not classify their source of infection and in one-fifth the information was missing.

Self-reported source of infection correlated with the types of activities reported in the ten days prior to testing positive (supplementary table 2).

Key performance indicators

Figure 2 shows results for four main KPIs, two for process (P6, percentage of test results returned on same or next day; P8, percentage of contacts notified on same or next day after interview with index) and two for outcomes (O1, percentage of new cases who were already in quarantine by time of positive test, i.e. new cases who were previously identified as contacts; O2, percentage of index cases in isolation by day of testing). The missing data for each KPI are outlined in supplementary table 5. Less than 1% of the data were missing for almost all KPIs, except for structure KPI S1 and process KPI P5 (7% and 5% missing data, respectively).

Structure indicators

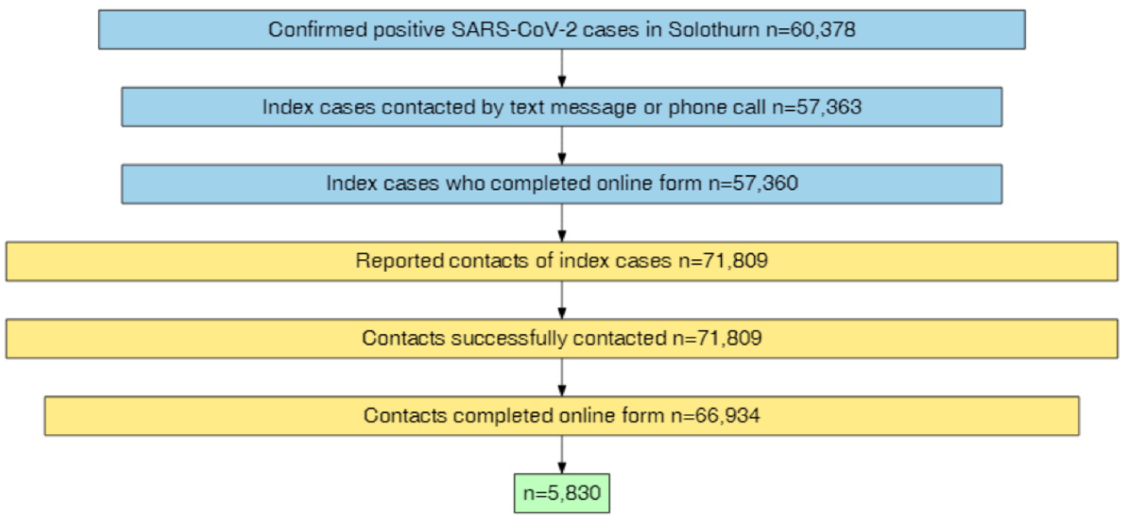
The CT workforce changed over time in response to the changing incidence rate of SARS-CoV-2 infection. The full-time equivalents of contact tracers increased from 35.4 to 36.3, decreased to 34.2 while delta was the dominant VOC, and then increased to 42.1 during the omicron wave (structure KPI S2, figure 3, supplementary table 4). Less than a third (28%) of index cases reported that they had installed the Swiss Covid app on their smartphone (structure KPI S1, supplementary table 4).

Process indicators

The process KPIs indicated that performance changed over the course of the pandemic. During the first waves of the pandemic and the period during which the alpha VOC was dominant, almost all test results were returned on the same or next day (process KPI P6, figure 2, supplementary table 4). The time taken to return PCR test results increased while delta was the dominant VOC and only partially recovered afterwards (process KPI P2, supplementary table 4 and supplementary figure 1B). Similarly, almost three-quarters of contacts were notified within 24 hours of the CT interview by phone with the index before the emergence of viral variants (process KPI P8, figure 2, supplementary table 4). While the alpha, delta and omicron VOCs were dominant, the proportions decreased to 64%, 36% and 54%. The days taken between the lab processing the result and the subsequent isolation of the index case also appeared to increase while delta was the dominant VOC (process KPI P4, supplementary figure 1D).

Nevertheless, the CT team successfully contacted almost all positive cases within 24 hours (99%) throughout the pandemic (process KPI P7, supplementary table 4). On average, at least 70% of new cases were tested and interviewed within 3 days of symptom onset across the entire

Figure 1: Contact tracing cascade in Solothurn from 15 November 2020 to 2 February 2022 (SARS-CoV-2 index cases and contacts). Boxes are sized in proportion to the number of individuals at each stage, except for the final box which is as narrow as the text allows.



The green box represents the contacts who tested positive for SARS-CoV-2 who became index cases.

period (process KPI P10). The contacts began quarantine a median of 3 days after the index case began experiencing symptoms (process KPI P3, supplementary table 4, supplementary figure 1C). This time period includes the time it

Table 1:
Characteristics of index cases referred to contact tracing in Solothurn from 15 November 2020 to 2 February 2022 by periods of different viral dominance.

Variable	Level	Pre-VOC	Alpha	Delta	Omicron	Entire period
		15 Nov 20 – 7 Feb 21*	**8 Feb 21 – 27 Jun 21**	**28 Jun 21 – 26 Dec 21**	**27 Dec 21 – 2 Feb 22**	**15 Nov 20 – 2 Feb 22**
Total		7494	4964	15,609	29,296	57,363
Age, years	0–17	503 (7%)	838 (17%)	4626 (30%)	7856 (27%)	13,823 (24%)
	18–29	1547 (21%)	1000 (20%)	2745 (18%)	6070 (21%)	11,362 (20%)
	30–39	1292 (17%)	879 (18%)	2582 (17%)	5355 (18%)	10,108 (18%)
	40–49	1116 (15%)	771 (16%)	2233 (14%)	4342 (15%)	8462 (14%)
	50–59	1385 (18%)	749 (15%)	1674 (11%)	3325 (11%)	7133 (12%)
	60–69	914 (12%)	440 (9%)	961 (6%)	1524 (5%)	3839 (7%)
	70–79	463 (6%)	189 (4%)	478 (3%)	492 (2%)	1622 (3%)
	≥80	271 (4%)	91 (2%)	300 (2%)	287 (1%)	949 (2%)
Gender	Female	3495 (51%)	2373 (48%)	7695 (49%)	13,748 (47%)	27,311 (48%)
	Male	3295 (49%)	2572 (52%)	7846 (50%)	14,085 (48%)	27,798 (49%)
	Other/unknown	0 (0%)	5 (0%)	57 (0%)	1455 (5%)	1517 (3%)
Symptoms**	Cough	3263 (44%)	2082 (42%)	7632 (49%)	13,175 (45%)	26,152 (46%)
	Runny nose	2701 (37%)	1571 (32%)	6662 (43%)	11,499 (39%)	22,433 (39%)
	Sore throat	2088 (28%)	1365 (28%)	4714 (30%)	11,360 (39%)	19,527 (34%)
	Fever	2253 (31%)	1369 (28%)	5271 (34%)	9714 (33%)	18,607 (33%)
	Sweating	1914 (26%)	1271 (26%)	4308 (28%)	8751 (30%)	16,244 (28%)
	General malaise	1422 (19%)	804 (16%)	2721 (17%)	5276 (18%)	10,223 (18%)
	Other symptoms	1799 (24%)	1050 (21%)	2737 (18%)	4424 (15%)	10,010 (18%)
	Loss of taste or smell	1698 (23%)	632 (13%)	2673 (17%)	1988 (7%)	6991 (12%)
	Nausea	765 (10%)	493 (10%)	1736 (11%)	3335 (11%)	6329 (11%)
	Diarrhoea	692 (9%)	416 (8%)	1283 (8%)	2146 (7%)	4537 (8%)
	Difficulty breathing or shortness of breath	570 (8%)	316 (6%)	902 (6%)	1586 (5%)	3374 (6%)
	Elevated heart rate	200 (3%)	83 (2%)	285 (2%)	491 (2%)	1059 (2%)
	Pneumonia	36 (0%)	17 (0%)	89 (1%)	34 (0%)	176 (0%)
	Acute respiratory distress	40 (1%)	8 (0%)	48 (0%)	40 (0%)	136 (0%)
	Oxygen required	4 (0%)	7 (0%)	6 (0%)	0 (0%)	17 (0%)
	Respiratory failure	6 (0%)	3 (0%)	1 (0%)	0 (0%)	10 (0%)
	No symptoms reported	1239 (17%)	1313 (27%)	3257 (21%)	3800 (15%)	9609 (18%)
Vaccination status***	Vaccinated (2 doses)	9 (0%)	233 (5%)	4246 (27%)	14,143 (48%)	18,631 (33%)

* See supplementary material for definition of periods of different viral variants.

** Note that some people experienced more than one symptom and so the percentages for symptoms reported do not add to 100%.

*** Cases answered the question “Are you fully vaccinated?”. Those who replied “Yes” were considered to be vaccinated with at least two doses.

VOC: variants of concern

Table 2:
Activities reported in the ten days prior to a positive SARS-CoV-2 test by individuals in Solothurn from 15 November 2020 to 2 February 2022 by time period of different viral dominance.

Activity*	Pre-VOC	Alpha	Delta	Omicron	Total
Fitness centre / sports	792 (4%)	1005 (8%)	2612 (7%)	2203 (5%)	6612 (6%)
Private party	1491 (7%)	442 (3%)	1677 (5%)	2213 (5%)	5823 (5%)
Work	1743 (8%)	956 (7%)	1705 (5%)	1339 (3%)	5743 (5%)
Dining with friends (home)	1494 (7%)	679 (5%)	1257 (3%)	2159 (5%)	5589 (5%)
Dining at a restaurant	817 (4%)	87 (1%)	1076 (3%)	1291 (3%)	3271 (3%)
Bar / club	113 (1%)	1 (0%)	591 (2%)	1027 (2%)	1732 (1%)
School	193 (1%)	199 (2%)	394 (1%)	253 (1%)	1039 (1%)
Sporting event (spectator)	3 (0%)	21 (0%)	366 (1%)	386 (1%)	776 (1%)
Choir/singing	10 (0%)	15 (0%)	348 (1%)	71 (0%)	444 (0%)
Foreign travel	30 (0%)	8 (0%)	125 (0%)	0 (0%)	163 (0%)
Public event	3 (0%)	0 (0%)	0 (0%)	0 (0%)	3 (0%)
Other	3220 (15%)	2731 (21%)	8343 (23%)	2611 (6%)	16,905 (14%)
Missing	11,711 (54%)	7065 (54%)	18,212 (50%)	33,806 (71%)	70,794 (60%)
Total	21,620 (100%)	13,209 (100%)	36,706 (100%)	47,359 (100%)	118,894 (100%)

* Some index cases reported more than one activity. Most index cases did not report any activities (n = 46,288; 81%).

VOC: variants of concern

takes to test the index case after symptom onset, the time to receive the results, and the time for CT and quarantine orders to be sent to contacts.

Index cases reported between 0 and 69 close contacts, although most did not report any (52%, n=29,754, process KPI P11). Two-thirds (65%) of index cases did not report any contacts in the pre-VOC period and the proportion steadily decreased to 40% in the omicron period (process KPI P9, figure 4). Of those who did report contacts, the median number (interquartile range [IQR]) of contacts for each period were 2 (1–4) for the pre-VOC periods and while alpha was the dominant VOC and 2 (1–3) for the periods during which delta and omicron were the dominant VOCs.

Outcome indicators

Figure 2: Process and outcome key performance indicators of contact tracing during the COVID-19 pandemic in the canton of Solothurn.The coloured solid lines indicate the percentage of the key performance indicators over time. The thicker black line shows the change in SARS-CoV2 caseload. The Greek symbols α, δ and o indicate the periods during which the alpha, delta and omicron SARS-CoV-2 variants of concern (VOCs), respectively, were dominant. The dashed line indicates the point at which the system contacted individuals automatically (1 January 2022).

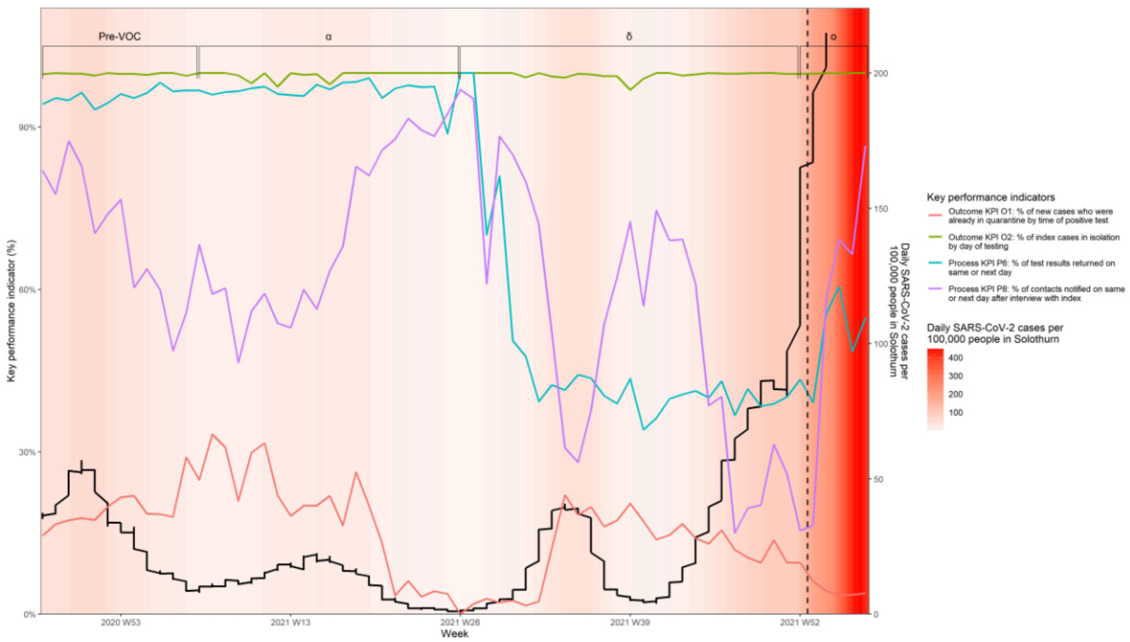
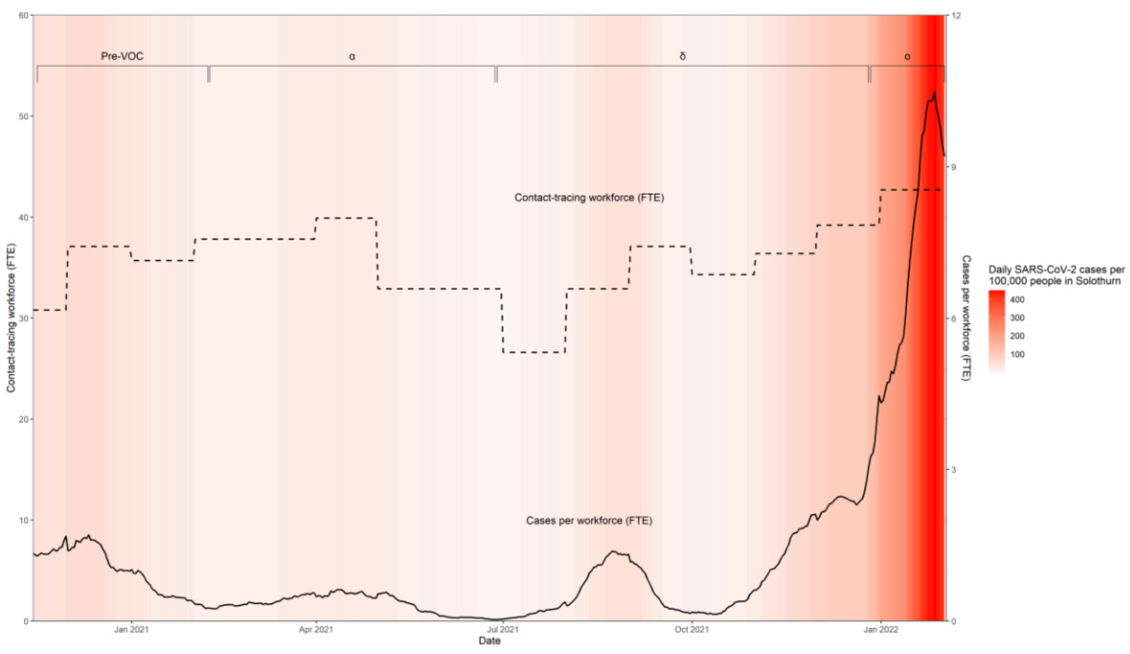


Figure 3: SARS-CoV-2 infections and the contact tracing workforce in the canton of Solothurn from 15 November 2020 to 2 February 2022, inclusive. The graph is shaded red according to the SARS-CoV-2 caseload. The dashed line indicates the contact-tracing workforce in full-time equivalent (FTE) and the solid line indicates the cases per workforce. The Greek symbols α, δ and o indicate the periods during which the alpha, delta and omicron SARS-CoV-2 variants of concern (VOCs), respectively, were dominant.



Overall, the percentage of index cases in isolation by day of testing remained at almost 100% throughout the period of analysis (outcome KPI O2, figure 2). However, the percentage of new cases already in quarantine by time of positive test, i.e. new cases who had previously been identified as contacts (outcome KPI O1) indicated that the CT system may have become less efficient as the pandemic continued. In the pre-VOC period and while alpha was the dominant VOC, about a fifth of index cases were already in quarantine by the time of the positive test (outcome KPI O1, figure 2, supplementary table 4). This percentage was highest (over 30% weekly) in February–March 2021 and lowest (<5% weekly) during May–August 2021. In the following waves, only 13% and 5% of index cases were already in quarantine (outcome KPI O1, supplementary table 4).

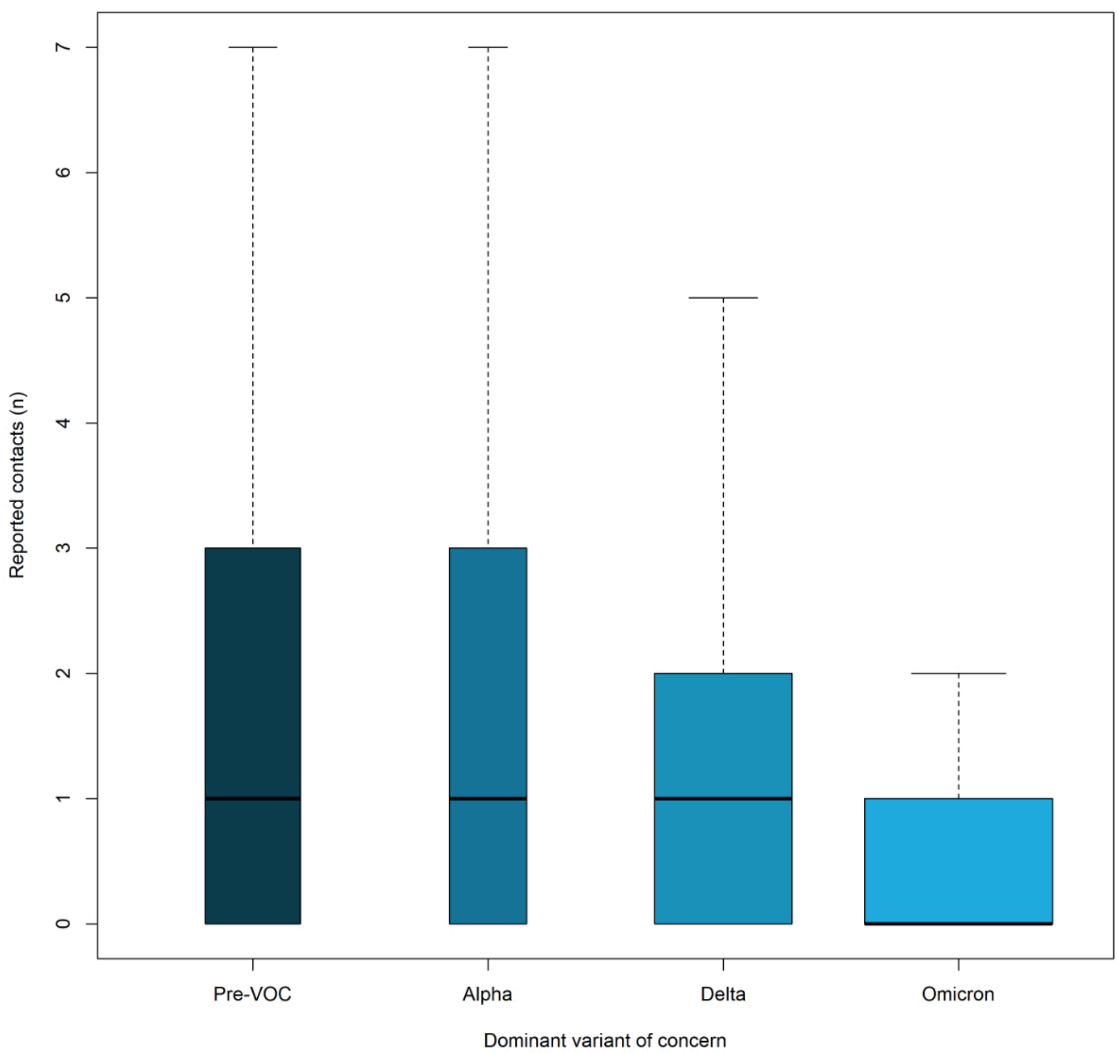
Nine percent of contacts tested positive for SARS-CoV-2 overall (outcome KPI O3, supplementary table 4). The proportion of contacts who tested positive for SARS-CoV-2 was highest during the period when alpha was the dominant VOC (13%) and lowest in the omicron wave (6%). From 31 May 2022 contacts who had been vaccinated or had tested positive in the 10–180 days before contact were exempt from quarantine and not under any obligation to get tested.

Discussion

The CT system in Solothurn used a partially automated workflow, which likely broke some chains of SARS-CoV-2 infection between 15 November 2020 and 2 February 2022, based on the high percentage of test results returned on the same or next day (KPI P6), the high percentage of contacts notified within 24 hours of the CT interview with the index (KPI P8), the high percentage of index cases in isolation by day of testing (KPI O2) and other indicators.

The two main process KPIs indicated that the system was faster during the earlier stages of the pandemic: more than 95% and 97% of test results were returned on the same or the next day during the period before the VOCs and while alpha was the dominant VOC (process KPI P6). However, during the periods when delta and omicron were the dominant VOCs, the percentages dropped to 41% and 52%, highlighting the burden placed on the overall system (test-

Figure 4: Number of contacts reported by SARS-CoV-2 index cases in Solothurn from 15 November 2020 to 2 February 2022. The horizontal bars indicate the median, the box indicates the interquartile range and the dashed lines indicate the minimum and maximum values, with outliers removed.



ing and CT) during periods of very high caseloads. Furthermore, a higher proportion of contacts was notified on the same day or next day after the interview with the index (process KPI P8) during the pre-VOC and alpha phases compared with the delta and omicron phases.

Interpretation of CT performance takes into consideration that the targets were proposed early in the COVID-19 pandemic and may not have been validated. Of the 16 KPIs that we assessed, 13 had at least one suggested target in the literature (supplementary table 3) [11–12, 22]. Five KPIs achieved the suggested targets overall and during each of the periods of different viral variants (process KPIs P1–3, P5 and P7; supplementary table 4, supplementary figure 1) and two had mixed results during the epidemic waves (process KPIs P4 and P6). The process KPIs P1–3 and P5 quantified the time taken between symptom onset, testing, lab results, isolation of the index and quarantine of the contact: all remained within the suggested targets of less than or equal to between one and five days. Process KPIs P4 and P6 were the only KPIs that varied widely from the suggested targets of ≤1 day and 90–100%, respectively. The median number of days between index test results and isolation was over one overall but remained at the target of one day for three out of four periods (process KPI P4).

Some KPIs that did not meet suggested targets indicate challenges at the testing laboratory and the CT workforce when delta and omicron were the dominant VOCs. Six KPIs were below the targets, according to the limited literature (structure KPI S2, process KPIs P8–10 and outcome KPIs O1 and O3). The caseload changed considerably during this period, so it was not clear what caused the test results to be delivered more slowly (process KPI P6). The number of people working in the CT team was below the suggested target of 30 tracers per 100,000 population, which corresponds to 64 FTE in Solothurn [11] (structure KPI S2). However, the number of tracers needed is debated and in addition to caseload depends on the degree of CT automation and team organisation, the level of personal contact required for interviews and telephone calls, and the availability of office space and funding. Less than 80% of contacts were notified on the same day or day after the interview with the index (process KPI P8), but the proportions were higher in the pre-VOC and alpha phases. More than 25% of cases did not report any contacts (process KPI P9), most likely due to the rising reluctance of the population to report contacts and the high volume of cases that restricted the ability of the CT team to contact index cases to verify information. Ultimately, it can be argued that above a certain number of cases per day and population, and particularly in the context of highly transmissible SARS-CoV-2 VOCs such as omicron, forward CT is no longer feasible. This is supported by a recent genomic analysis of sequences obtained in 2020, which found that CT likely slowed transmission during the summer of 2020, when there were few cases, but not during the second wave in autumn/winter 2020-2021, when there was a very high number of cases [24]. Therefore, public health experts support focusing on cluster identification and outbreak investigations when cases are rising [3–4].

The outcome indicators are closest to measuring the containment of COVID-19 by CT activities. The main outcome KPI O2 which indicated the percentage of index cases in isolation by day of testing remained high throughout the pandemic (almost 100% in all time periods), whereas the proportion of new cases who were already in quarantine by the time of the positive test (outcome KPI O1) was relatively low (range 5–22%). The target of 80% has been suggested [12], but not validated. We observed that less than 80% of new cases were already in quarantine by the time of the positive test. It is feasible that many residents would leave the canton on an almost daily basis for work or education. Contacts who were resident in other regions of Switzerland were under the jurisdiction of a separate canton and thus it was not possible to link many index cases and contacts. Therefore, we expect that the percentage may be misleadingly low because the data were not linked with other regions in Switzerland. Furthermore, according to the suggested target, we observed that 9% of contacts overall tested positive for SARS-CoV-2, higher than a target proportion of <1% (outcome KPI O3). However, this target is not validated and may result in a larger number of contacts being quarantined.

Contact tracers in other countries reported similar findings to ours. Contact tracers in the United States and Spain found that the performance of CT was worse while caseloads were higher [25–26]. The US team cited overwhelmed staff, unable to conduct thorough interviews due to time pressure, as a possible reason [25]. They also found that different viral dynamics in new variants complicated CT because of increased transmissibility and possibly shorter incubation period [25]. The Catalonian team responded by increasing their workforce [26]. They promote the use of constant monitoring using KPIs to allow for regular evaluation of the CT system and the epidemiological situation [26]. In another US study, contact tracers in New York were able to use their data to confirm that there was more SARS-CoV-2 transmission at known places of interest in the city [27]. Some reports on CT highlighted areas where we might have improved data collection. For example, the US team collected objective data on test results from contacts to monitor the contacts' outcomes: the prevalence ratio of SARS-CoV-2 infection was much higher in contacts compared with non-contacts when viral transmission was higher in the community [25]. In Taiwan, they benefitted from centralised digital tools, with a unique nationwide CT platform, linking various data sources, including information from telephone companies, and using a smartphone-based real-time locating system to track contacts [7]. The CT team reported a subsequent increase in self-reported updates of health status from 22.5% to 61.5% via automatic text message or web applications in Taiwan during the COVID-19 pandemic (7), reducing the pressure on the CT workforce.

Our study provides an overview of a new digitised CT system established in an urgent and ever-changing real-life situation and proposes a set of important KPIs for evaluation purposes. To our knowledge, we present the first analysis to transparently report the performance of a CT workflow in Switzerland. The strengths of this analysis were the availability of CT data over a long period of 15 months, nearly the entire period of CT in the canton of Solothurn. The dataset includes the CT workforce data and covers periods of different viral VOCs. However, the study is limited by data that are self-reported, missing or not requested.

For example, we noticed that people became less willing to disclose information on infection sources and did not report activities as readily as the pandemic progressed. In contrast, index cases reported more close contacts in the later stages, but that may be because most of the close contacts had recovered or had been vaccinated and were therefore no longer ‘at risk’ of being quarantined (vaccinated and recovered persons could be exempted from quarantine from 31 May 2021). Reporting morale likely decreased and many index cases decided to circumvent the system by notifying friends and family themselves. A further limitation is that the CT system only covers the canton of Solothurn, which may not reflect other cantons and other CT workflows. However, the canton of Solothurn is a mid-sized canton, with demographics representative of Switzerland. We did not have access to data from other Swiss cantons for comparison.

CT is a useful tool for reducing the transmission of infectious diseases when the incidence rate is below a manageable threshold. This description of CT in a Swiss canton illustrates how partial automation of CT contributed to real-time monitoring and surveillance of SARS-CoV-2 throughout the pandemic. The findings support the use and monitoring of CT data to inform modelling studies and public health measures in real time. Sudden exponential increases in caseloads challenged the system although automation ensured that CT could continue. Our study also shows the need for standardised benchmarks across CT to facilitate cross-region and cross-border cooperation, taking into account the resource level of the country, which will require an electronic data capture system to allow real-time data extraction. Adding genomics data to the CT workflow might further support and advance identification of transmission clusters [15, 24, 28]. Digitised CT workflows can be used for other existing or re-emerging infectious diseases such as measles or mpox, but also for emerging infections in the years to come [28]. In the context of pandemic preparedness, we believe that periods of relatively low transmission provide a good opportunity to analyse and compare CT performance, to improve the systems and to reach a consensus on targets. Modelling studies could help public health authorities to understand where to focus attention to maximise interruption of transmission. Efficient CT systems should automate workflows as far as possible to adapt to high incidence rates, save on human resources, and generate KPIs to monitor the system’s performance.

Acknowledgments

We would like to thank all persons who contributed data to this study. We are also indebted to the cantonal physician’s office of the canton of Solothurn and the contact tracing team for their diligent daily work and the immense efforts to continuously improve the CT workflow.Authors' contributions: Conception and design: LH, CM, NL, LF. Contact tracing data collection: CM, EB, BD, LF. Statistical analysis: LH, CM. Wrote the first draft of the paper and revised it based on comments from all authors: LH, CM, NL, LF. All authors reviewed and approved the final version of the manuscript.

Financial disclosure

LF is supported by the National Institute of Allergy and Infectious Diseases (NIAID) through grant no. 5U01-AI069924-05. LH was supported by the Swiss National Science Foundation (grant no. 176233) and the European Union Horizon 2020 research and innovation programme (grant no. 101003688).

Potential competing interests

All authors have completed and submitted the International Committee of Medical Journal Editors form for disclosure of potential conflicts of interest. No potential conflict of interest related to the content of this manuscript was disclosed.

References

1. Aleta A, Martín-Corral D, Pastore Y Piontti A, Ajelli M, Litvinova M, Chinazzi M, et al. Modelling the impact of testing, contact tracing and household quarantine on second waves of COVID-19. Nat Hum Behav. 2020 Sep;4:964–71. http://dx.doi.org/10.1038/s41562-020-0931-9.
2. Kucharski AJ, Klepac P, Conlan AJ, Kissler SM, Tang ML, Fry H, et al.; CMMID COVID-19 working group. Effectiveness of isolation, testing, contact tracing, and physical distancing on reducing transmission of SARS-CoV-2 in different settings: a mathematical modelling study. Lancet Infect Dis. 2020 Oct;20(10):1151–60. http://dx.doi.org/10.1016/S1473-3099(20)30457-6.
3. Kojaku S, Hébert-Dufresne L, Mones E, Lehmann S, Ahn YY. The effectiveness of backward contact tracing in networks. Nat Phys. 2021 May;17:652–8. http://dx.doi.org/10.1038/s41567-021-01187-2.
4. Raymenants J, Geenen C, Thibaut J, Nelissen K, Gorissen S, Andre E. Empirical evidence on the efficiency of backward contact tracing in COVID-19. Nat Commun. 2022 Aug;13(1):4750. http://dx.doi.org/10.1038/s41467-022-32531-6.
5. Ashcroft P, Lehtinen S, Bonhoeffer S. Test-trace-isolate-quarantine (TTIQ) intervention strategies after symptomatic COVID-19 case identification. PLoS One. 2022 Feb;17(2):e0263597. http://dx.doi.org/10.1371/journal.pone.0263597.
6. 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 Dec;48(12):1451–6. http://dx.doi.org/10.1016/j.ajic.2020.08.012.
7. 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 Dec;101:348–52. http://dx.doi.org/10.1016/j.ijid.2020.09.1483.
8. 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 Nov;2(11):e607–21. http://dx.doi.org/10.1016/S2589-7500(20)30184-9.
9. World Health Organization. Digital tools for COVID-19 contact tracing: annex: contact tracing in the context of COVID-19, 2 June 2020 [Internet]. World Health Organization; 2020 [cited 14 December 2022]. Available from: https://apps.who.int/iris/handle/10665/332265
10. Daniore P, Ballouz T, Menges D, von Wyl V. The SwissCovid Digital Proximity Tracing App after one year: were expectations fulfilled? Swiss Med Wkly. 2021 Sep;151(35-36):w30031. http://dx.doi.org/10.4414/SMW.2021.w30031.
11. Vogt F, Kurup KK, Mussleman P, Habrun C, Crowe M, Woodward A, et al. Contact tracing indicators for COVID-19: rapid scoping review and conceptual framework. PLoS One. 2022 Feb;17(2):e0264433. http://dx.doi.org/10.1371/journal.pone.0264433.
12. Frieden T. COVID Contact Tracing Indicator list for consideration [Unpublished work]. 2020.
13. Donabedian A. The quality of care. How can it be assessed? JAMA. 1988 Sep;260(12):1743–8. http://dx.doi.org/10.1001/jama.1988.03410120089033.
14. Federal Office of Public Health FOPH. Coronavirus: Measures and ordinances [Internet]. Federal Office of Public Health FOPH; 2022 [cited September 20 2022]. Available from: https://www.bag.admin.ch/bag/en/home/krankheiten/ausbrueche-epidemien-pandemien/aktuelle-ausbrueche-epidemien/novel-cov/massnahmen-des-bundes.html
15. Anderegg N, Schwab T, Borcard L, Mugglin C, Keune-Dübi B, Ramette A, et al. Population-based SARS-CoV-2 whole genome sequencing and contact tracing during the COVID-19 pandemic in Switzerland. J Infect Dis. 2023;228(3):251-260. http://dx.doi.org/10.1093/infdis/jiad074.
16. Kanton Solothurn. Bevölkerungszahlen [Internet]. Kanton Solothurn; 2022 [cited 20 September 2022]. Available from: https://so.ch/verwaltung/finanzdepartement/amt-fuer-finanzen/statistikportal/bevoelkerung/bevoelkerungszahlen/
17. Federal Office of Public Health FOPH. Communicable Diseases Legislation – Epidemics Act, (EpidA) [Internet]. Bern: Federal Office of Public Health; 2020 [cited 13 December 2021]. Available from: https://www.bag.admin.ch/bag/en/home/gesetze-und-bewilligungen/gesetzgebung/gesetzgebung-mensch-gesundheit/epidemiengesetz.html
18. Federal Office of Public Health FOPH. COVID-19 Switzerland [Internet]. Swiss Confederation; 2022 [cited 21 October 2022]. Available from: https://www.covid19.admin.ch/en/epidemiologic/

19. World Health Organization. Tracking SARS-CoV-2 variants [Internet]. 2022 [cited 12th August 2022]. Available from: https://www.who.int/activities/tracking-SARS-CoV-2-variants/
20. CumulusPro. Straatos. CumulusPro; 2022.
21. GmbH SP. Menschen. Prozesse. Digitalisierung. . Lenzburg: Strub & Partner GmbH; 2022.
22. Resolve to Save Lives. Covid-19 Contact Tracing Playbook [Internet]. 2022 [cited 11 August 2022]. Available from: https://contacttracingplaybook.resolvetosavelives.org/checklists/metrics
23. Federal Office of Public Health FOPH. Coronavirus: SwissCovid app [Internet]. 2023. Available from: https://www.bag.admin.ch/bag/en/home/krankheiten/ausbrueche-epidemien-pandemien/aktuelle-ausbrueche-epidemien/novel-cov/swisscovid-app-und-contact-tracing.html
24. Nadeau SA, Vaughan TG, Beckmann C, Topolsky I, Chen C, Hodcroft E, et al. Swiss public health measures associated with reduced SARS-CoV-2 transmission using genome data. Sci Transl Med. 2023;15(680):eabn7979. http://dx.doi.org/10.1126/scitranslmed.abn7979.
25. Borah BF, Pringle J, Flaherty M, Oeltmann JE, Moonan PK, Kelso P. High Community Transmission of SARS-CoV-2 Associated with Decreased Contact Tracing Effectiveness for Identifying Persons at Elevated Risk of Infection – Vermont. Clin Infect Dis. 2022;75(S2):S334-7. http://dx.doi.org/10.1093/cid/ciac518.
26. Herrero M, Ciruela P, Mallafré-Larrosa M, Mendoza S, Patsi-Bosch G, Martínez-Solanas È, et al.; Epidemiological Surveillance Network of Catalonia. SARS-CoV-2 Catalonia contact tracing program: evaluation of key performance indicators. BMC Public Health. 2022 Jul;22(1):1397. http://dx.doi.org/10.1186/s12889-022-13695-8.
27. Pei S, Kandula S, Cascante Vega J, Yang W, Foerster S, Thompson C, et al. Contact tracing reveals community transmission of COVID-19 in New York City. Nat Commun. 2022 Oct;13(1):6307. http://dx.doi.org/10.1038/s41467-022-34130-x.
28. Walker A, Houwaart T, Finzer P, Ehlkes L, Tyshaieva A, Damagnez M, et al.; German COVID-19 OMICS Initiative (DeCOI). Characterization of Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) Infection Clusters Based on Integrated Genomic Surveillance, Outbreak Analysis and Contact Tracing in an Urban Setting. Clin Infect Dis. 2022 Mar;74(6):1039–46. http://dx.doi.org/10.1093/cid/ciab588.

Appendix

Supplementary table 1: Age and gender of index cases referred to contact tracing in Solothurn from 15th November 2020 to 2nd February 2022 compared with population in Switzerland and the canton of Solothurn

Variable		Index cases in Solothurn*	Swiss population†	Canton of Solothurn†
Total		57,363 (100%)	8,606,033 (100%)	275,247 (100%)
Age (years)	0-17	13,823 (24%)	1,459,411 (17%)	44,321 (16%)
	18-29	11,362 (20%)	1,182,347 (14%)	36,895 (13%)
	30-39	10,108 (18%)	1,226,598 (14%)	37,280 (14%)
	40-49	8,462 (15%)	1,195,237 (14%)	35,369 (13%)
	50-59	7,133 (12%)	1,302,707 (15%)	43,806 (16%)
	60-69	3,839 (7%)	980,369 (11%)	35,408 (13%)
	70-79	1,622 (3%)	752,048 (9%)	25,253 (9%)
	>80	949 (2%)	507,316 (6%)	16,915 (6%)
Gender	Female	27,798 (49%)	4,337,170 (50%)	137,659 (50%)
	Male	27,311 (48%)	4,268,863 (50%)	137,588 (50%)

*Index cases referred to contact tracing in Solothurn from 15th November 2020 to 2nd February 2022

†Swiss population data comes from the Federal Statistical Office in 2020 (https://www.bfs.admin.ch/bfs/en/home/statistics.html)

Supplementary table 2: Activities reported in the ten days prior to testing positive for SARS-CoV-2 by the self-reported source of infection in index cases in Solothurn from 15th November 2020 to 2nd February 2022

		Type of activity reported*												
		Dining with friends (at home)	Eating in restaurant	Private party	Bar / club	Choir/ singing	School	Work	Fitness centre / sports	Public event	Sporting event (spectator)	Foreign travel	Other	None reported
Self-reported source of infection†	Family or friends	647	173	533	52	10	47	296	309	1	32	9	962	17500
	School	89	38	94	10	34	169	154	434	0	23	0	555	4996
	Work	79	65	60	19	4	1	514	62	0	7	1	248	3437
	Shopping/public transport	31	27	29	8	2	3	53	39	0	4	3	291	2328
	Other	161	217	364	405	41	14	153	332	0	93	74	1244	4062
	Unknown	183	134	175	33	11	28	215	250	0	19	10	580	9070

* Numbers in each cell have been coloured conditionally according to the numbers in each column: green indicates a higher number. For example, the highest number of people reporting dining with friends as an activity reported family or friends as their likely source of infection.

† 5,013 index cases had missing data for their self-reported source of infection.

Supplementary table 3. Published benchmarks of key performance indicators of contact tracing in relation to COVID-19

Category	Key performance indicator	Source from literature	Benchmarks from literature
Structure	S1. Proportion of index cases who reported installing the Swiss Covid app	COVID contact tracing indicator list for consideration [1]	NA
	S2. Number of people working in the contact tracing team (full time equivalent)	-	30 tracers per 100,000 population [2] No other published literature available
Process	P1. Days between case symptom onset and diagnosis of the index case	[3]	≤ 3days [3]
	P2. Days between index case test and results	[3]	≤ 2 days [3]
	P3. Days between case symptom onset and quarantine start of contacts	[3]	≤ 5 days [3]
	P4. Days between test results and isolation of index case	[3]	≤ 1 day [3]

Category	Key performance indicator	Source from literature	Benchmarks from literature
	P5. Days between isolation of index case and quarantine of contact	[3]	≤1 day [3]
	P6. Percentage of test results returned on same or next day	COVID contact tracing indicator list for consideration [1]	Percentage of cases being reached within one day of receiving a positive lab result - Target: 90% [2] Increasing towards 100% [1]
	P7. Percentage of index cases contacted on same or next day after the test result	COVID contact tracing indicator list for consideration [1]	90% [1]
	P8. Percentage of contacts notified on same or next day after interview with index	COVID contact tracing indicator list for consideration [1]	80% [1]
	P9. Percentage of cases with no contacts elicited	COVID contact tracing indicator list for consideration [1]	<25% [2]
	P10. Out of new symptomatic cases, percentage tested and interviewed within 3 days of onset of symptoms	COVID contact tracing indicator list for consideration [1]	80% [1]

Category	Key performance indicator	Source from literature	Benchmarks from literature
	P11. Number of contacts per case	COVID contact tracing indicator list for consideration [1]	NA
Outcome	O1. Percentage of new cases who were already in quarantine by time of positive test (i.e., new cases who were previously identified as contacts), out of all index cases	COVID contact tracing indicator list for consideration [1]	Increasing weekly, to 80% (reversed target of metric ‘percentage of new cases unlinked to a source of infection’) [1]
	O2. Percentage of index cases in isolation by day of testing, out of all index cases	COVID-19 contact tracing indicator list for consideration [1]	NA
	O3. Percentage of contacts who tested positive for SARS-CoV-2, out of all elicited contacts	[2]	Percentage of contacts of SARS-CoV-2 positive contacts who become SARS-CoV-2 positive - Target: <1% [2]

S, structure; P, process; O, outcome; NA, not available

Supplementary table 4. Key performance indicators by time period of different viral dominance

Category	KPI	Numerator/ denominator	Pre-VOC	Alpha	Delta	Omicron	Overall
Structure	S1. Proportion of index cases who reported installing the Swiss Covid app	Number of index cases using app/All index cases	2,110/7,494 = 28%	935/4,964 = 19%	3,680/15,609 = 24%	9,309/29,296 = 32%	16,034/57,363 = 28%
	S2. Number of people working in the contact tracing team (FTEs), mean	Number of people working equivalent to full-time hours by calendar month	35.4	36.3	34.2	42.1	35.8
Process	P1. Days between case symptom onset and diagnosis of the index case, median (IQR)	Date of test result – date of symptom onset in index cases, calculated for all index cases	2 (1, 4)	2 (1, 4)	2 (1, 4)	2 (1, 3)	2 (1, 3)
	P2. Days between index case test and results, median (IQR)	Date of test result – date of test in index cases, calculated for all index cases	1 (0, 1)	1 (0, 1)	2 (1, 3)	1 (1, 2)	1 (1, 2)
	P3. Days between case symptom onset and quarantine start of	Date of symptom onset in index cases – start of quarantine of contacts, calculated for all contacts	3 (2, 4)	3 (2, 4)	3 (2, 5)	3 (2, 4)	3 (2, 4)

Category	KPI	Numerator/ denominator	Pre-VOC	Alpha	Delta	Omicron	Overall
	contacts, median (IQR)[1]						
	P4. Days between test results and isolation of index case, median (IQR)	Date of test result – date of start of isolation, calculated for all index cases	1 (1, 2)	1 (1, 2)	2 (1, 3)	1 (1, 2)	2 (1, 2)
	P5. Days between isolation of index case and quarantine of contact, median (IQR)[1]	Date of start of quarantine of index cases – date of start of isolation of contacts, calculated for all contacts	0 (-1, 1)	0 (-1, 1)	1 (0, 2)	1 (0, 2)	1 (0, 2)
	P6. Percentage of test results returned on same or next day	Number of index cases who received their test results within 24 hours/All index cases	7,112/7,494 = 95%	4,808/4,964 = 97%	6,461/15,609 = 41%	15,163/29,296 = 52%	33,544/57,363 = 58%
	P7. Percentage of index cases contacted on same or next day after the test result	Number of index cases who were contacted within 24 hours of their test result/All index cases	7,448/7,494 = 99%	4,953/4,964 = 100%	15,530/15,609 = 99%	29,131/29,296 = 99%	57,062/57,363 = 99%

[1] On 31.05.2021, quarantine was no longer required for contacts who had been vaccinated. Quarantine dates are also recorded for contacts who were deemed to exempt from quarantine.

Category	KPI	Numerator/ denominator	Pre-VOC	Alpha	Delta	Omicron	Overall
	P8. Percentage of contacts notified on same or next day after interview with index[2]	Number of contacts who were notified within 24 hours of the interview with the index case/All contacts	9,979/13,771 = 72%	5,381/8,444 = 64%	7,071/19,793 = 36%	13,163/24,253 = 54%	35,594/66,261 = 54%
	P9. Percentage of cases with no contacts elicited	Number of index cases who reported no contacts/All index cases	4,897/7,494 = 65%	2,902/4,964 = 58%	8,053/15,609 = 52%	11,753/29,296 = 40%	27,605/57,363 = 48%
	P10. Out of new symptomatic cases, percentage tested and interviewed within 3 days of onset of symptoms	Number of index cases tested within 3 days of symptom onset/All symptomatic index cases	4,233/6,090 = 70%	2,518/3,552 = 71%	8,431/12,083 = 70%	17,188/21,971 = 78%	32,370/43,693 = 74%
	P11. Number of contacts per case, median (IQR)	Number of contacts per index case, calculated for all index cases	1 (0, 3)	1 (0, 3)	1 (0, 2)	0 (0, 1)	0 (0, 2)

[2] During the pre-VOC period and when the alpha and delta VOCs were dominant, contact tracers conducted an in-depth telephone interview with the index cases and manually checked the contact data. During the omicron wave, contacts were registered through the online form only and then automatically contacted without prior manual checking by contact tracers.

Category	KPI	Numerator/ denominator	Pre-VOC	Alpha	Delta	Omicron	Overall
Outcome	O1. Percentage of new cases who were already in quarantine by time of positive test [3]	Number of index cases who used to be contacts/Total number of index cases	1,391/7,494 = 19%	1,096/4,964 = 22%	2,005/15,609 = 13%	1,338/29,296 = 5%	5,830/57,363 = 10%
	O2. Percentage of index cases in isolation by day of testing	Number of index cases in isolation on or before day of testing/All index cases	7,459/7,494 = 100%	4,933/4,964 = 99%	15,557/15,609 = 100%	29,255/29,296 = 100%	57,204/57,363 = 100%
	O3. Percentage of contacts who tested positive for SARS-CoV-2	Number of contacts who tested positive/All contacts	1,391/13,771 = 10%	11,096/8,444 = 13%	2,005/19,793 = 10%	1,338/24,253 = 6%	5,830/66,261 = 9%

KPI, key performance indicator; VOC, variants of concern; FTE, full time equivalent; IQR, interquartile range.

[3] The percentage of new cases who were already in quarantine by time of positive test may be underestimated since definition of contacts and quarantine rules changed over time. During the omicron period, contacts were notified automatically and no telephone interview was performed with index patients. Please note that some contacts came from other cantons or countries and were not linked with index cases, therefore they are not included here.

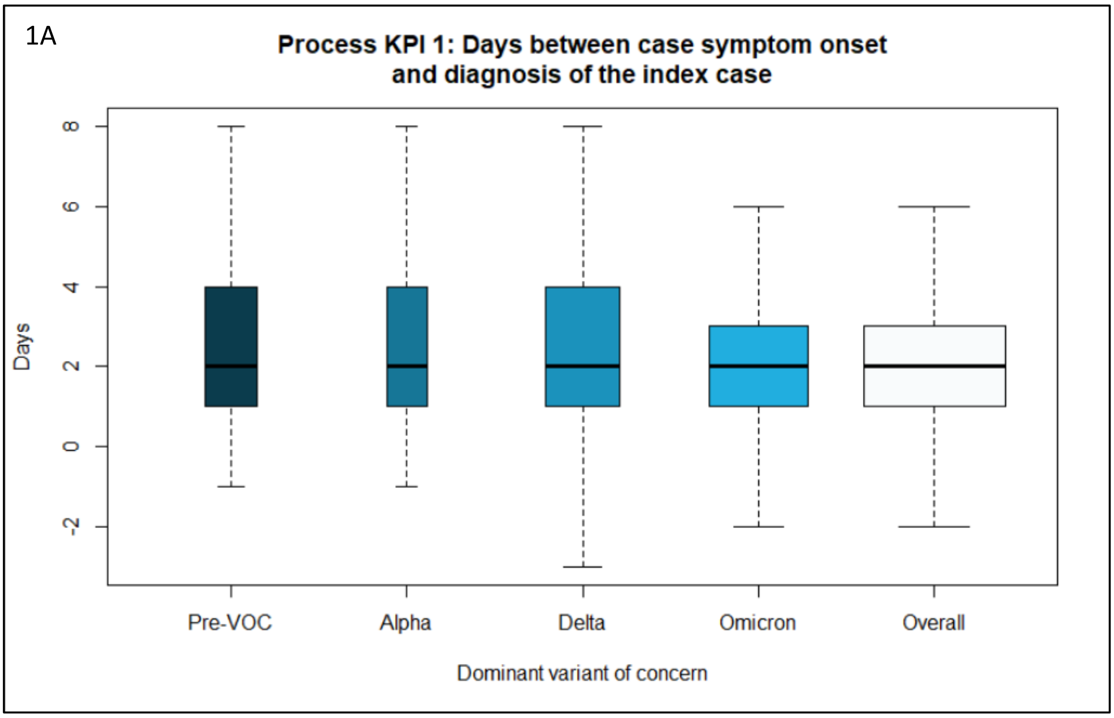
Supplementary table 5. Missing values in key performance indicator variables

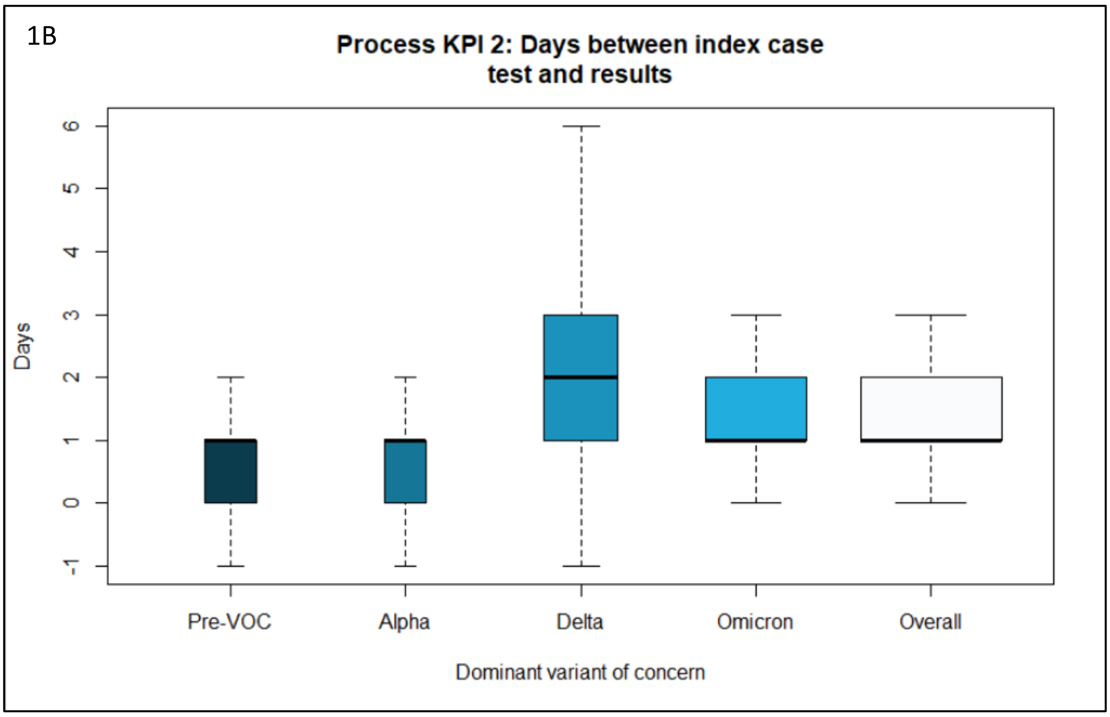
Category	KPI	Variable name	Missing values		Variables used to create KPI (n, % missing)
			n	%	
Structure	S1. Proportion of index cases who reported installing the Swiss Covid app	KPI12	4,160/57,363	7%	ct_so_index$Appavailable (4,160/57,363, 7%)
	S2. Number of people working in the contact tracing team (full time equivalent)	KPI13	NA	NA	No data missing
Process	P1. Days between case symptom onset and diagnosis of the index case	KPI1	650/43,692 (symptomatic index cases only)	1%	ct_so_index$Date.Receipt.Lab (44/43,692, 0.1%)
					ct_so_index$DateStartSymptoms (615/43,692, 1%)
	P2. Days between index case test and results	KPI2	95/57,363	0.2%	ct_so_index$Date.Receipt.Lab (72/57,363, 0.1%)
					ct_so_index$Test.Date (51/57,363, 0.1%)
	P3. Days between case symptom onset and quarantine start of contacts	KPI3	477/54,097 (symptomatic index cases only)	0.9%	ct_so_contacts_index$KP_Case_Date (0/54,097, 0%)
					ct_so_contacts_index$DateStartSymptoms (477/54,097, 0.9%)
	P4. Days between test results and isolation of index case	KPI4	136/57,363	0.2%	ct_so_index$Date.Receipt.Lab (72/57,363, 0.1%)
					ct_so_index$Isolation_Start (78/57,363, 0.1%)
	P5. Days between isolation of index case and quarantine of contact	KPI5	3408/66,261	5%	ct_so_contacts_index$Quar_StartDatee (3,358/66,261, 5%)
					ct_so_contacts_index$Isolation.Starts (57/66,261, 0.1%)
	P6. Percentage of test results returned on same or next day	KPI6	95/57,363	0.2%	ct_so_index$Date.Receipt.Lab (72/57,363, 0.1%)
					ct_so_index$Test.Date (51/57,363, 0.1%)

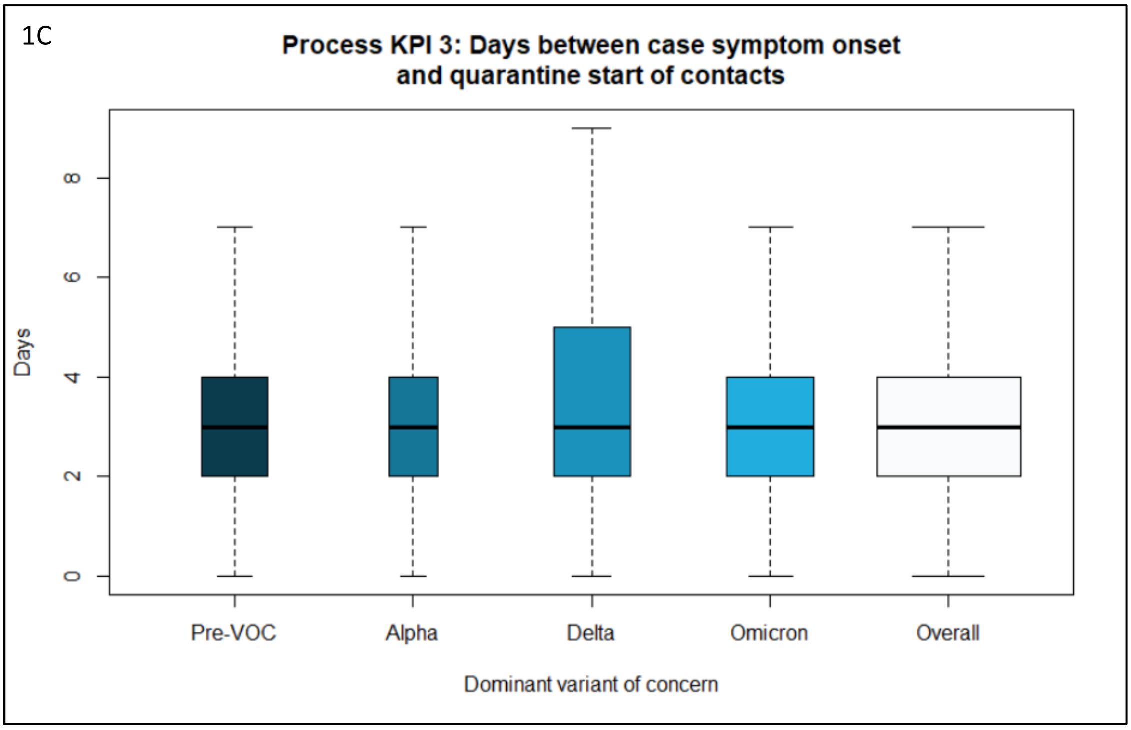
Category	KPI	Variable name	Missing values		Variables used to create KPI (n, % missing)
			n	%	
	P7. Percentage of index cases contacted on same or next day after the test result	KPI7	72/57,363	0.1%	ct_so_index$Case_Date (0/57,363, 0%)
					ct_so_index$Date.Receipt.Lab (72/57,363, 0.1%)
	P8. Percentage of contacts notified on same or next day after interview with index	KPI8	0/66,261	0%	ct_so_contacts_index$KP_Case_Date (0/66,261, 0%)
					ct_so_contacts_index$Case_Date (0/66,261, 0%)
	P9. Percentage of cases with no contacts elicited	KPI9	0/57,363	0%	ct_so_contacts_index$IP_DocID (0/66,261, 0%)
	P10. Out of new symptomatic cases, percentage tested and interviewed within 3 days of onset of symptoms	KPI10	615/43,692 (symptomatic index cases only)	0.01%	ct_so_index$Case_Date (0/43,692, 0%)
					ct_so_index$DateStartSymptoms (615/43,692, 0.01%)
					ct_so_index$AnySymptom (0/43,692, 0%)
	P11. Number of contacts per case	nContacts	0/57,363	0%	ct_so_index$nContacts (0/57,363, 0%)
Outcome	O1. Percentage of new cases who were already in quarantine by time of positive test (i.e., new cases who were previously identified as contacts)	KPI14	4/5,907 (total contacts who tested positive)	0.1%	conversion_ct$IP.DocID (4/5,907, 0.1%)
	O2. Percentage of index cases in isolation by day of testing	KPI16	93/57,363	0.2%	ct_so_index$Test.Date (51/57,363, 0.1%)
					ct_so_index$Isolation_Start (78/57,363, 0.1%)
	O3. Percentage of contacts who tested positive for SARS-CoV-2	prev_contact	0/57,363	0%	ct_so_index$prev_contact (0/57,363, 0%)

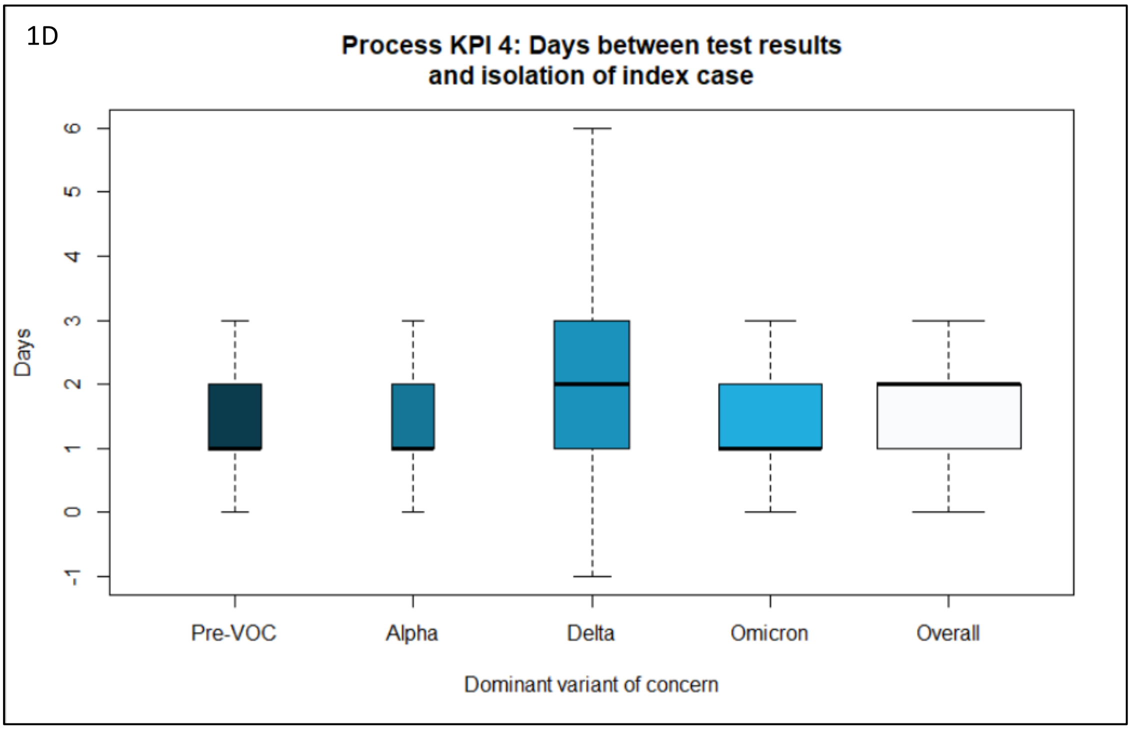
KPI, key performance indicator.

Supplementary figure 1. Boxplots of selected process key performance indicators by period of different viral dominance and overall

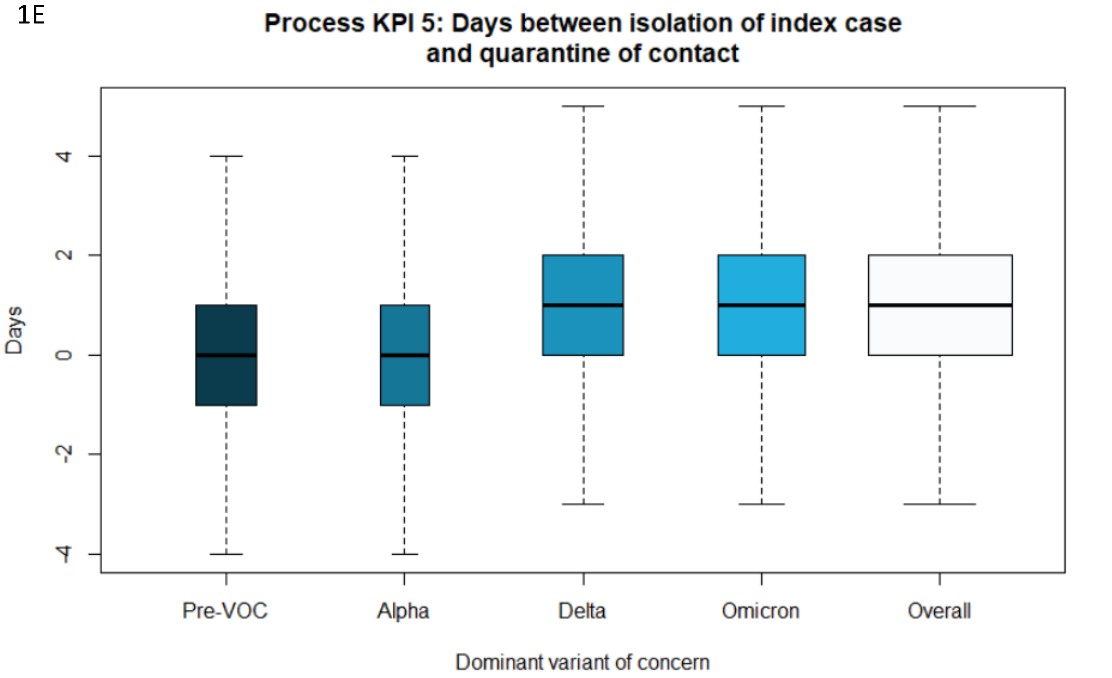





1C
Process KPI 3: Days between case symptom onset
and quarantine start of contacts
Days
0
2
4
6
8
Pre-VOC
Alpha
Delta
Omicron
Overall
Dominant variant of concern


1D
Process KPI 4: Days between test results
and isolation of index case
Days
-1
0
1
2
3
4
5
6
Pre-VOC
Alpha
Delta
Omicron
Overall
Dominant variant of concern

1E



Process KPI 5: Days between isolation of index case
and quarantine of contact
Days
4
2
0
-2
-4
Pre-VOC
Alpha
Delta
Omicron
Overall
Dominant variant of concern

Supplementary File 1: Detailed information on contact tracing practices, data collection system, and definitions.

Definitions

We defined an index case as an individual who tested positive for SARS-CoV-2 by a polymerase chain reaction (PCR) from 15 November 2020 (or an antigen test from November 2021) according to the test criteria set by the Federal Office of Public Health (FOPH), and with a legal residency in the Swiss canton of Solothurn. Temporary visitors had to notify the FOPH if they tested positive for SARS-CoV-2 while in Switzerland. They were given relevant advice by the FOPH or the canton in which they were staying. Index cases were required to isolate for 10 days either from the date of the positive test result or the date of symptom onset. This period for isolation and quarantine was reduced to five days from 13th January 2022 [4].

Close contacts were defined as individuals who had either spent at least 15 minutes with an index case at a distance of less than 1.5 metres without wearing a face mask or were living in the same household as the index case in the two days prior to testing positive, according to the recommendations by the FOPH [4]. The contact tracing (CT) system automatically matched names, dates of birth and mobile numbers of new index cases to identify those who had been previously identified as close contacts and subsequently tested positive during their quarantine. We included close contacts with a legal residency in the canton of Solothurn who were reported by index cases from the canton of Solothurn and elsewhere.

We describe the performance of the CT system by periods in which different viral variants were dominant because they each corresponded to a large wave of infection. We defined periods of dominance using data from the CoVariants website [5]. The alpha variant became dominant on 8th February 2021, which was followed by the delta variant on 28th

June 2021 and the omicron variant on 27th December 2021. We defined the pre-VOC period from 15th November 2020 to 7th February 2021, alpha period from 8th February 2021 to 27th June 2021, delta period from 28th June to 26th December 2021 and the omicron period from 27th December 2021 to the end of the study period on 2nd February 2022.

Contact tracing practices and digital CT workflow

The CT team collected data from index cases and contacts by in-depth telephone interviews and collation of self-reported information from online forms, based on the Epidemics Act and the FOPH. After the first epidemic wave in spring 2020, the public health authorities of the canton of Solothurn, together with other cantons in Switzerland, implemented the Surveillance Outbreak Response Management & Analysis System (SORMAS) [6, 7] software. Due to the need of a more automated workflow, the public health authorities of the canton of Solothurn implemented the process-oriented CT software "Straatos" just before the start of the second epidemic wave in October 2020. This was customized in-house software solution to meet the requirements of the canton and the regulations and recommendations of the FOPH. Adaptions to the software were made when new recommendations on isolation or quarantine were introduced at the national level [4]. When the caseloads increased, capacity was increased by asking the current workforce to work overtime and increase their current workload (immediate response) and by recruiting more contact tracers (short-term response).

Index cases received a link via text message to an online form after testing positive. Index cases reported their age, sex, place of residence, symptoms, date of symptom onset, potential source of infection, vaccination status, close contacts, and places visited prior to symptom onset or positive test if asymptomatic. The CT system then automatically emailed the index case an 'administrative order', authorised by the cantonal physician, which ordered the individual to isolate, based on the Epidemics Act [8]. The CT staff telephoned index cases within one day of their positive test result to confirm their responses to the online form.

Afterwards, the contact tracer would discuss the information provided with another member of staff. The index cases were automatically contacted again by text message at the end of isolation on day ten (until 12th January 2022) or on day five (from 13th January 2022) to report any symptoms. There was a three-step ‘traffic light’ system with levels one (indicating a low caseload and high staff availability) to four (indicating high caseload and low staff availability) to determine the extent to which staff would individually contact the index cases and contacts, check vaccination documents and test orders, and implement CT in institutional and business settings (Supplementary file 3). The levels were not objectively defined; usually, the level increased at the beginning of a wave of infection. For example, at levels one and two, the CT staff contacted the index cases on days six and ten. However, at level three they only contacted them on these days when there were sufficient resources and at level four, they did not contact them on these days.

Close contacts identified through forward CT received a text message with a link to an online form. The text of the message instructed them to stay at home in quarantine and get tested five days after their last contact with the index case. Contacts reported their age, sex, vaccination status, workplace or school, and email address. Contacts were also emailed an ‘administrative order’ [8]. The email included information on what to do in case they developed symptoms, current recommendations by the FOPH, links to the FOPH website, and a telephone number and email address if they needed more information. The contacts were called by telephone in the first two days of quarantine and at the end of the quarantine, depending on the case load (Supplementary file 3). Contacts received an automated text message on day five of quarantine to remind them to get tested. At the onset of the omicron wave (27th December 2021), the workload was judged to be too high to continue to call contacts at the start of the quarantine period by telephone. From January 2021, contacts could leave quarantine on day 7, provided they tested negative for SARS-CoV-2. After this date, contacts were only telephoned at the end of quarantine in exceptional circumstances.

The CT team in Solothurn used backward tracing, as well as forward tracing, from the 15th November 2020. Index cases reported locations and events visited in the 10 days prior to testing positive using an online form (Supplementary table 2 and file 2) and reviewed during the telephone interview. The CT software automatically indicated index patients that could belong to a cluster because of attending the same event, bar, school, nursing home, or sharing a residential building. In addition, when capacity allowed, the CT team contacted the venues at which index cases had reported visiting in the ten days prior to infection. Based on this information, a mobile testing team (run by the two cantonal testing centres) were sent out.

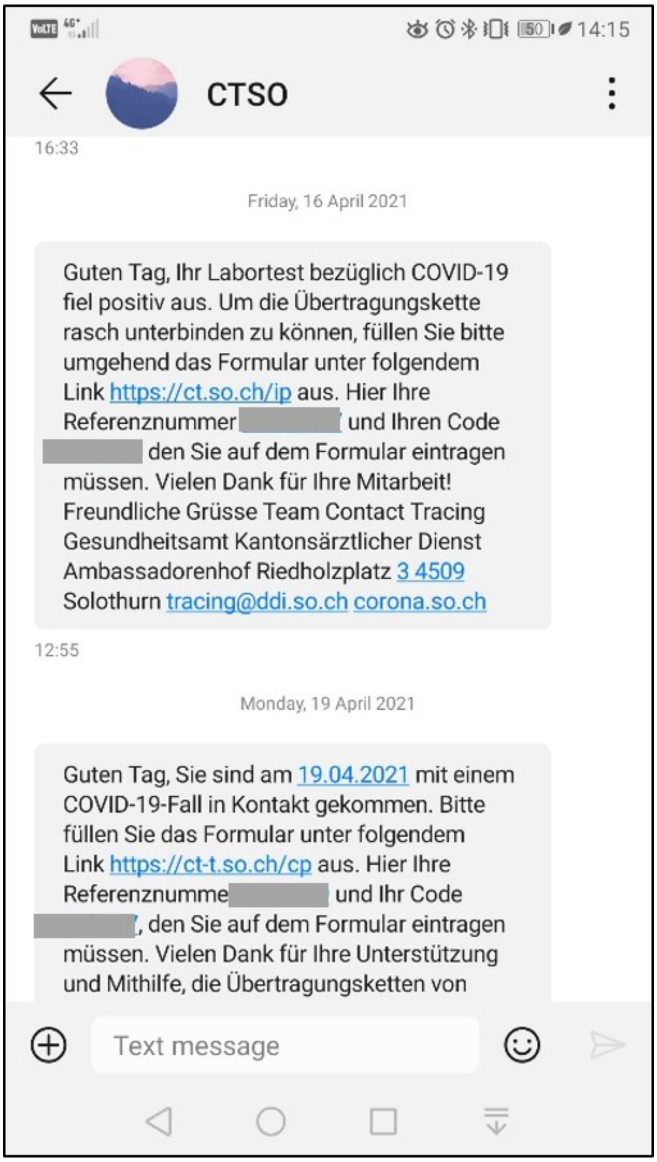
Supplementary file 2: Workflow of the partially automated contact tracing, canton of Solothurn, 2020-22.

We present an overview of the general workflow as well as specific workflows for schools, nursing homes, and travel returnees below.

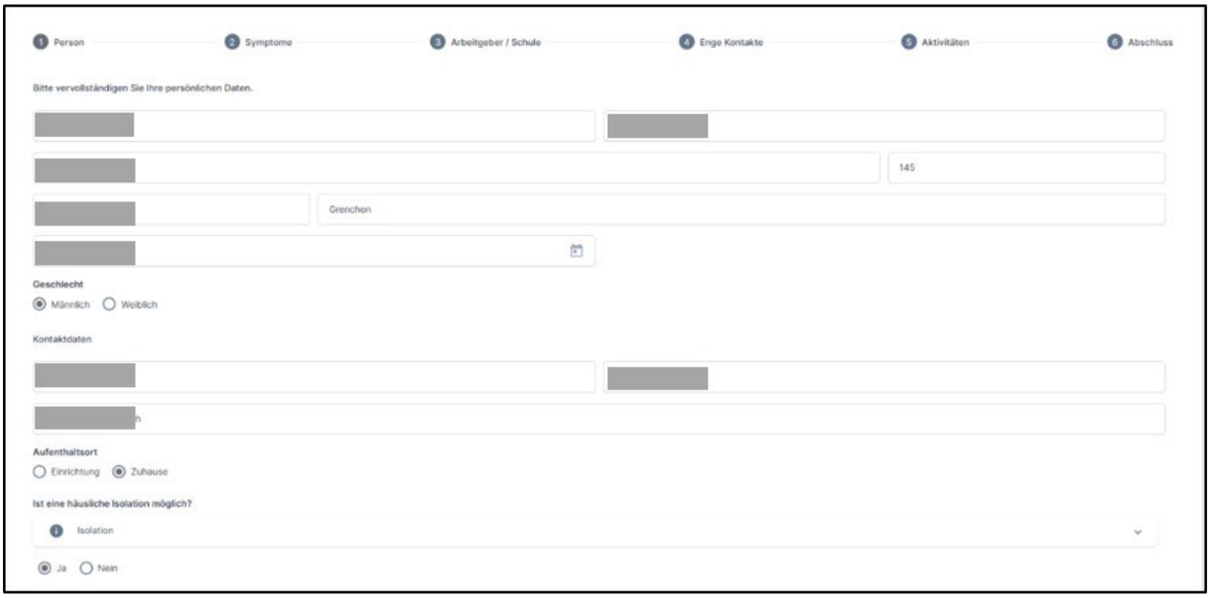
General workflow

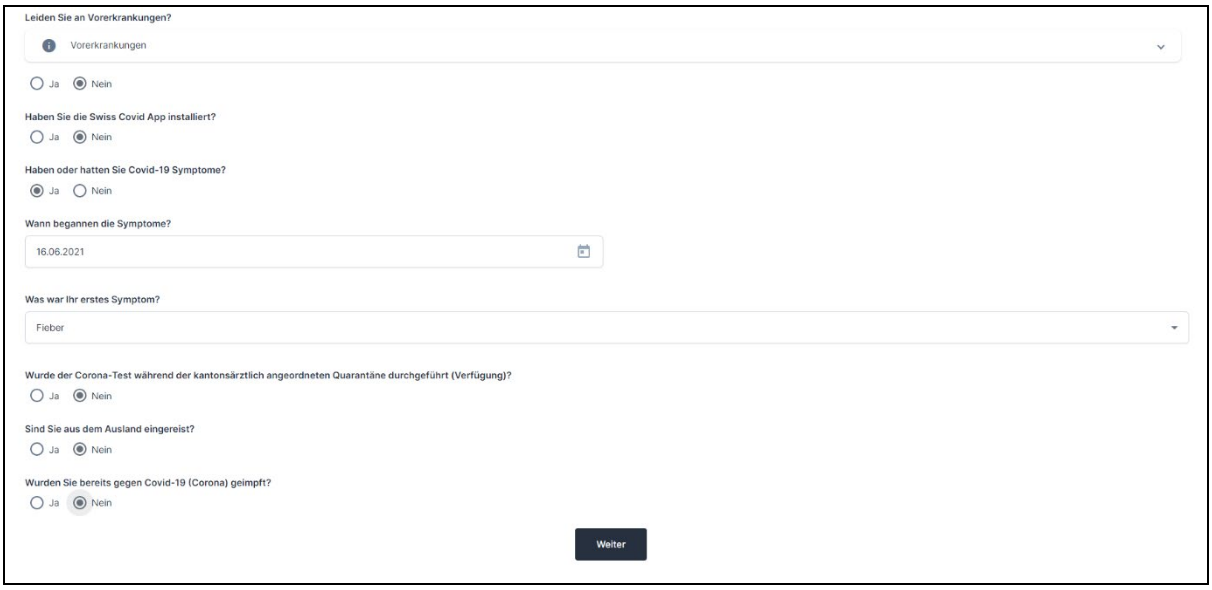
1. Laboratories report positive SARS-CoV-2 test results to a national information system, which subsequently sends a notification to the cantonal contact tracing (CT) system. The CT system opens a new case.

2. The CT system automatically sends a message to the index case via text message or email, depending on which contact details are available in the national information system.

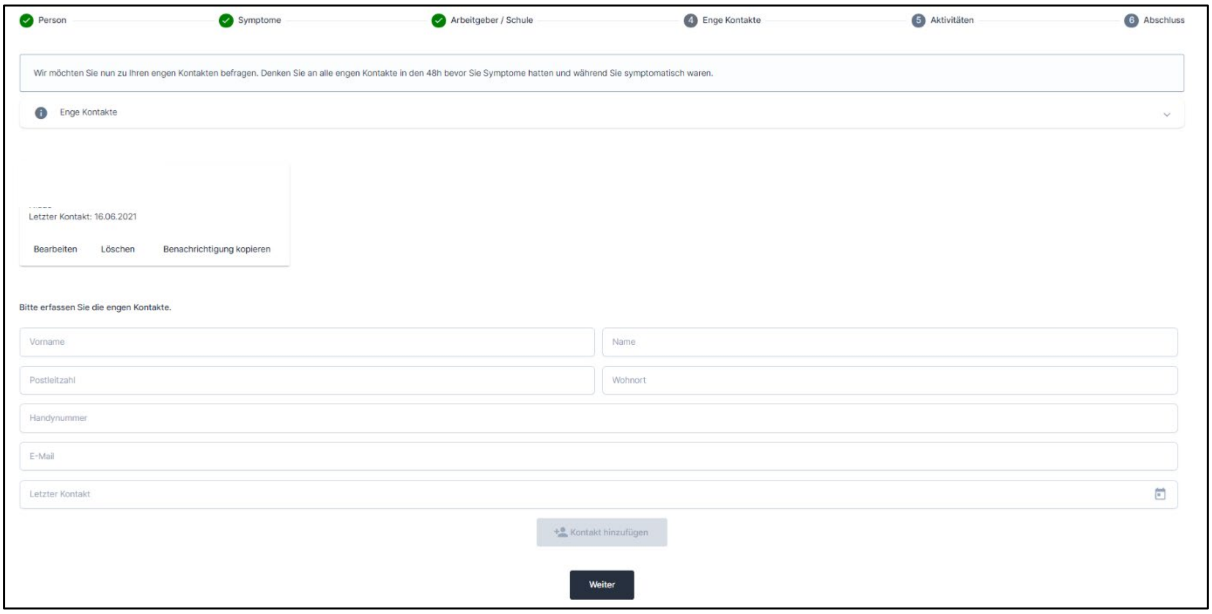


3. The sent message contains a link to an online form that the index case is asked to complete. The form contains six parts.

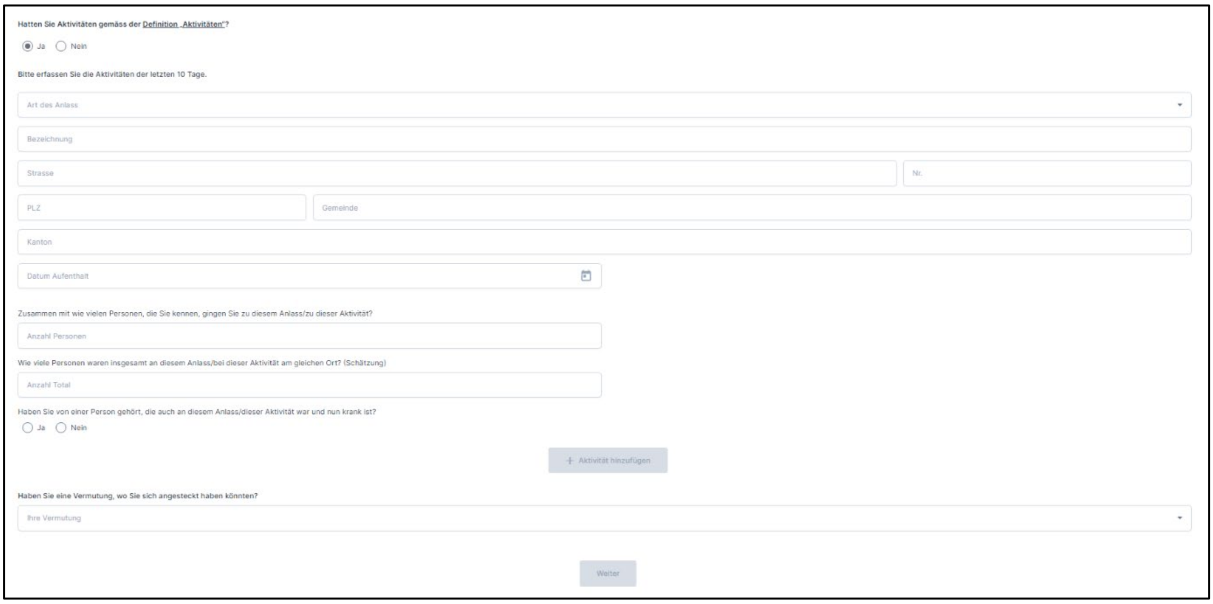




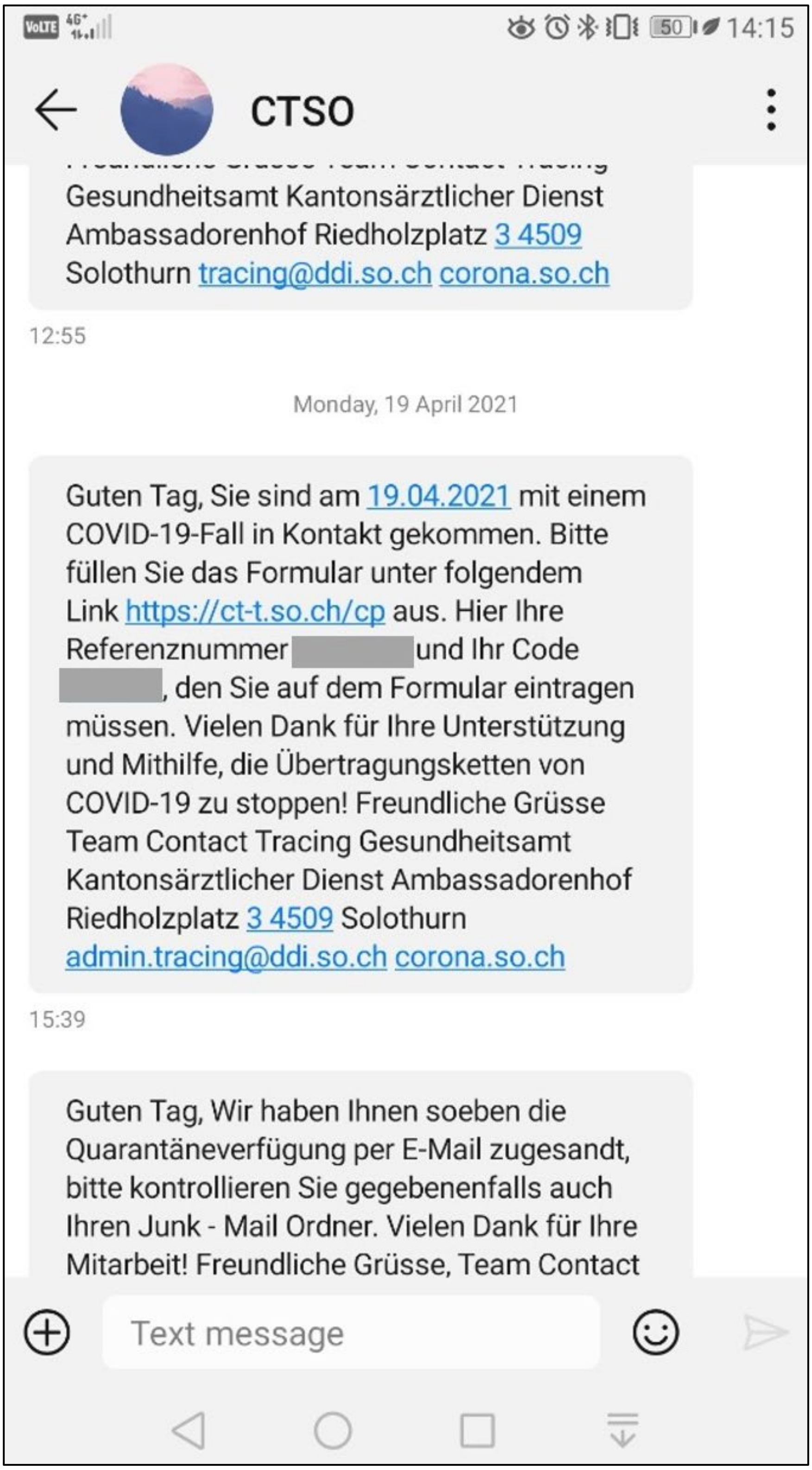
4. The index case give the contact information of their close contacts.



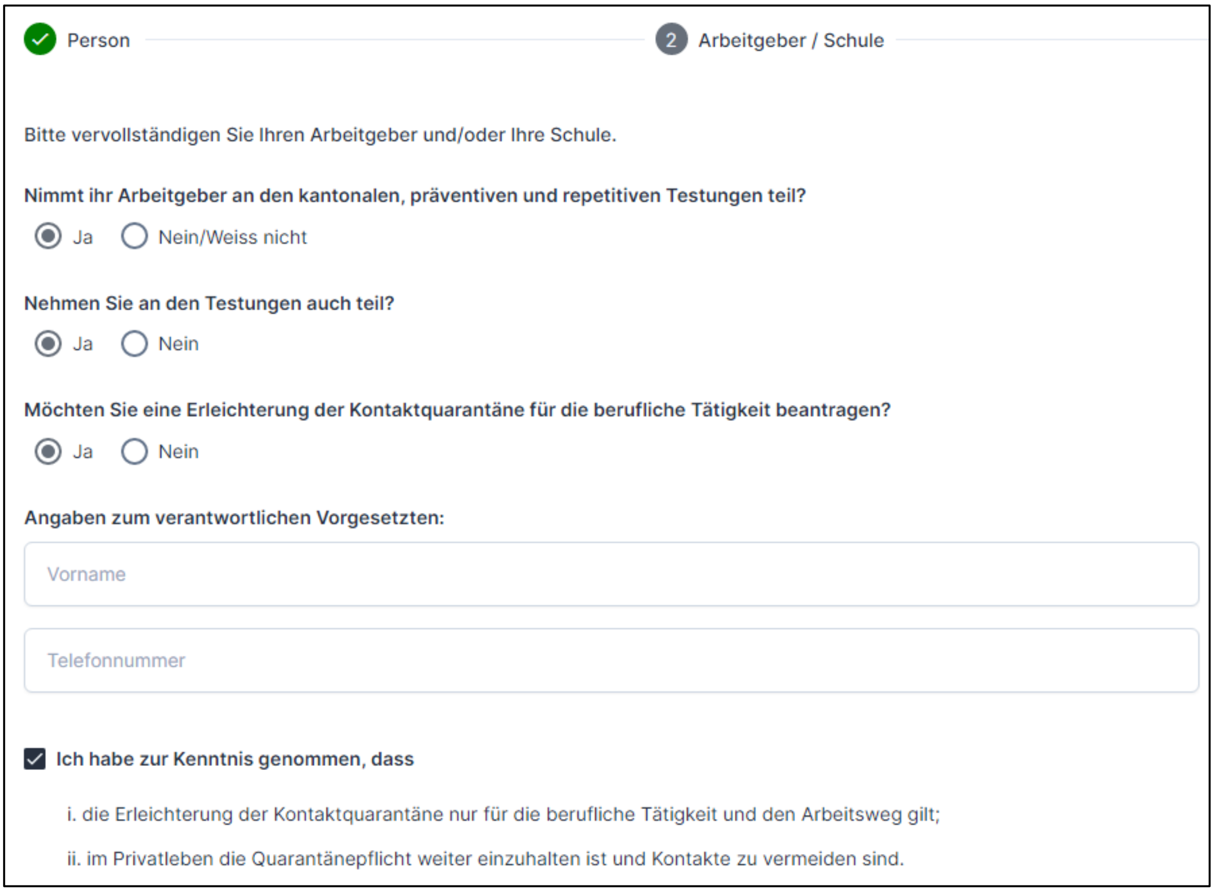
5. Finally, the index cases are asked to record all activities (e.g., bar visit, private party) from the ten days prior to the COVID-19 diagnosis. The CT team reviews and completes the online forms during telephone interviews with the index cases.



6. The reported close contacts (see step 3) are also sent a link to an online form via text message and asked to complete it.



7. The contacts complete the online form and the CT team subsequently telephone the contacts to review and complete the forms.



Person

2 Arbeitgeber / Schule

Bitte vervollständigen Sie Ihren Arbeitgeber und/oder Ihre Schule.

Nimmt ihr Arbeitgeber an den kantonalen, präventiven und repetitiven Testungen teil?

(●) Ja ( ) Nein/Weiss nicht

Nehmen Sie an den Testungen auch teil?

(●) Ja ( ) Nein

Möchten Sie eine Erleichterung der Kontaktquarantäne für die berufliche Tätigkeit beantragen?

(●) Ja ( ) Nein

Angaben zum verantwortlichen Vorgesetzten:

Vorname

Telefonnummer

[x] **Ich habe zur Kenntnis genommen, dass**

i. die Erleichterung der Kontaktquarantäne nur für die berufliche Tätigkeit und den Arbeitsweg gilt;

ii. im Privatleben die Quarantänepflicht weiter einzuhalten ist und Kontakte zu vermeiden sind.

Special workflows

If a new positive SARS-CoV-2 case is associated with a **school, nursing home, history of travel, or health care facility**, based on information in the online forms, the system assigns an automatic warning. A specialised CT team handles such cases.

Example email from the Solothurn CT team:


tracing@ddi.so.ch [redacted]

Warnung IP Schule / Kindergarten / Krippe - [redacted]

_ighaa Schulen Tracing

Guten Tag,

Gemäss den Regeln des Contact Tracing bezüglich der Branche der Arbeitgeber möchten Sie über folgende

[redacted]

Fallnummner:

[redacted]

Symptom Beginn:

[redacted]

Adresstyp Spezifikation (Arbeitsgebiet)

Schule / Kindergarten / Krippe

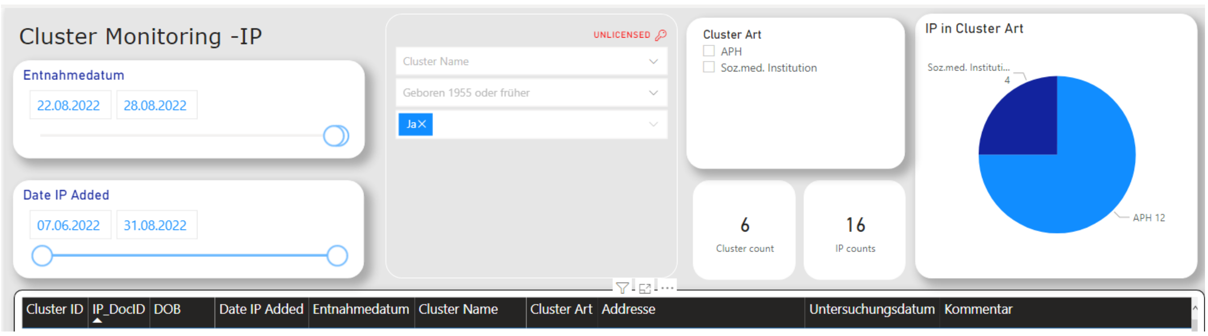
[redacted]

Weitere Angaben (Arbeitgeber)

[redacted]

The CT team can also access a virtual dashboard which gives an overview of CT in Solothurn.

Cluster monitoring in the CT software identified cases that were potentially linked with each other by comparing home address, employer, self-reported source of infection. The CT team could also manually assign a case to a specific cluster. The CT team further investigated potential clusters of cases.



Supplementary file 3: Contingency planning "traffic light system" for the gradual adjustment of contact tracing due to increasing case numbers and temporarily insufficient staff.

Level 1 to 4 correspond to the caseload – Level 1 representing low caseload, level 4 very high caseload. The colours indicate the the adjustment of contact tracing. Green: action will be performed, Yellow: action is only carried out if there are sufficient resources, Red: action will no longer be carried out.

Process	**Step**	**Level 1**	**Level 2**	**Level 3**	**Level 4**
Index case flow	Send “administrative order” for isolation	Green	Green	Green	Green
	Telephone contact day 0 -2	Green	Green	Green	Green
	Phone contact day 6	Green	Green	Yellow	Red
	Phone contact day 10	Green	Green	Yellow	Red
Contact person flow	Send “administrative order” for quarantine	Green	Green	Green	Green
	Lift contact quarantine 2G	Green	Green	Yellow	Yellow
	Control proof (before lifting)	Green	Yellow	Red	Red
	Control proof (after lifting)	Green	Green	Yellow	Yellow
	Lift contact quarantine during working time	Green	Yellow	Red	Red
	Telephone contact day 0 - 2	Green	Green	Yellow	Red
	Send test recommendation / test arrangement	Green	Green	Green	Green
	Control test recommendation / test arrangement	Green	Yellow	Red	Red
	Partial control test recommendation / test arrangement	Green	Green	Red	Red
	Phone contact day 6	Green	Yellow	Yellow	Red
	Shorten contact quarantine	Green	Green	Yellow	Yellow
	Control Test shortening (beforehand)	Green	Yellow	Red	Red
	Control Test Shortening (retrospective)	Green	Green	Red	Red
	Contact day 10	Green	Yellow	Yellow	Red
Contact person of contact	Recording	Green	Yellow	Red	Red
	Send test recommendation / test arrangement	Green	Yellow	Red	Red

Process	Step	Level 1	Level 2	Level 3	Level 4
	Control test recommendation / test arrangement				
	Partial control test recommendation / test arrangement				
Travel return	Send “administrative order” for quarantine after returning from high risk country				
	Lift entry quarantine 2G				
	Control proof (before lifting)				
	Control proof (after lifting)				
	Shipping test recommendation / test arrangement				
	Control test recommendation / test arrangement				
	Partial control test recommendation / test arrangement				
	Phone contact day 6				
	Shorten entry quarantine				
	Control test shortening (beforehand)				
	Control Test Shortening (retrospective)				
Institutions	Control protection concept				
	Outbreak investigation				
	Shipping test recommendation / test arrangement				
	Control test recommendation / test arrangement				
	Dispose isolation due to outbreak investigation				
	Order quarantine due to outbreak investigation				
	Shipping test order due to outbreak investigation				
	Control test arrangement due to outbreak investigation				
Sequencing	Arrange sequencing				
	Review sequencing results				

Process	Step	Level 1	Level 2	Level 3	Level 4
	Intensified tracing				
Events	Notification				
	Shipping test recommendation / test arrangement				
	Control test recommendation / test arrangement				

References

1. Frieden T. COVID Contact Tracing Indicator list for consideration [Unpublished work]. 2020.
2. Vogt F, Kurup KK, Mussleman P, Habrun C, Crowe M, Woodward A, et al. Contact tracing indicators for COVID-19: Rapid scoping review and conceptual framework. PLoS One. 2022;17(2):e0264433.
3. Resolve to Save Lives. Covid-19 Contact Tracing Playbook [Internet]. 2022 [cited 11 August 2022]. Available from: https://contacttracingplaybook.resolvetosavelives.org/checklists/metrics.
4. Federal Office of Public Health FOPH. Coronavirus: Measures and ordinances [Internet]. Federal Office of Public Health FOPH; 2022 [cited September 20 2022]. Available from: https://www.bag.admin.ch/bag/en/home/krankheiten/ausbrueche-epidemien-pandemien/aktuelle-ausbrueche-epidemien/novel-cov/massnahmen-des-bundes.html.
5. Hodcroft E. Overview of Variants in Countries [Internet]. [cited 30 November 2022]. Available from: https://covariants.org/per-country?region=Switzerland&country=Region+3.
6. Silenou BC, Verset C, Kaburi BB, Leuci O, Ghozzi S, Duboudin C, et al. A Novel Tool for Real-time Estimation of Epidemiological Parameters of Communicable Diseases Using Contact-Tracing Data: Development and Deployment. JMIR Public Health and Surveillance. 2022;8(5):e34438.
7. SORMAS Foundation [Internet]. 2022 [cited 29 November 2022]. Available from: https://sormas.org/.
8. Federal Office of Public Health FOPH. Communicable Diseases Legislation – Epidemics Act, (EpidA) [Internet]. Bern: Federal Office of Public Health; 2020 [cited 13 December 2021]. Available from: https://www.bag.admin.ch/bag/en/home/gesetze-und-bewilligungen/gesetzgebung/gesetzgebung-mensch-gesundheit/epidemiengesetz.html.