Contact tracing different age groups during the COVID-19 pandemic: a retrospective study from south-west Germany

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Abstract

Background: Contact tracing was used in many countries during the initial waves of the COVID-19 pandemic to prevent disease spread, reduce mortality and avoid the overburdening of health care systems. In many countries, including Germany, entirely new systems were employed to trace and quarantine potentially infected persons.

Objective: Using data collected in the Rhine-Neckar district and Heidelberg city (RNK/HD) in south-west Germany (population 706 974), this study examines differences and the overall effectiveness and efficiency of contact tracing within different age groups and waves of the pandemic.

Methods: From 27 January 2020 until 30 April 2022, the Heidelberg and Rhein-Neckar Public Health Authority routinely collected data on COVID-19 infection, quarantine and death. To assess variations in the proportion, risk and relative risk of infection, quarantine and deaths, data was grouped into age groups (young: 0-19; adult: 20-65; and elderly: >65 years) and by date of pandemic waves. The overall effectiveness and efficiency of contact tracing was determined for different age groups and timepoints by calculating the quarantine sensitivity (proportion of infected population captured in quarantine) and positive predictive value (PPV; proportion of quarantined population that were infected).

Results: Within the study period and location, 28.0% of the population tested SARS-CoV-2 positive, 11.1% were quarantined, and 0.123% died following an infection. Compared to adults, the relative risk of infection was lowest for the elderly (RR: 0.400; 95%CI: 0.394-0.406), and initially lower for young people before increasing (first wave RR: 0.523; 95%CI: 0.458-0.597; all waves RR: 1.35; 95%CI 1.34-1.36). Over 90% of COVID-19 associated deaths occurred amongst elderly people, with no associated deaths amongst young people. Elderly people had the lowest risk of quarantine compared to adults (RR: 0.474; 95%CI: 0.462-0.487), while young people had the highest risk (RR to adults: 2.69; 95%CI: 2.65-2.72). During the first three waves of the pandemic, contact tracing captured from between 28.0% to 46.4% of all infections in quarantine (sensitivity), with 5.91% to 23.4% of the quarantined population testing positive for COVID-19 (PPV).

Conclusions: Data from RNK/HD supports national and international research showing that quarantine was an important and effective infection control measure prior to the introduction of the vaccine. Increased use of quarantine in the first three waves of the pandemic was consistent with the established risks of COVID-19 infection and death. However, the disproportional use of quarantine was inconsistent with the risks of infection or death in specific age groups, and unsupported by emerging knowledge of transmission pathways, incidence of long-COVID or other risks. More generally, however, quarantine sensitivity and PPV measurements demonstrate how contact tracing systems were increasingly effective in capturing more of the infected population in quarantine, and increasingly efficient in raising the proportion of infections within the quarantine population.

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Introduction

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) was first identified as the causative agent for the respiratory disease known as COVID-19 in the Hubei Province of Wuhan, China, in December 2019 [1, 2]. Since then until 30 April 2022, over half a billion cases of COVID-19 and over 6 million COVID-19 related deaths have been reported worldwide [3].

COVID-19 in Germany

The first COVID-19 case in Germany was identified in Munich on 27 January 2020. By the end of April 2022, Germany, with a population of around 83 million, had registered over 24 million COVID-19 cases, with over 135,000 COVID-19 associated fatalities. While the disease affected all age groups, close to 90% of all COVID-19 related deaths in Germany were in persons aged over 60, and over 98% in persons aged over 50 [4]. According to Germany's national public health institute, the Robert Koch Institute (RKI), the majority of the initial SARS-CoV-2 infections in Germany occurred in six distinct waves, each dominated by one of four variants of the virus [5].

Within the first two wild-type dominated waves of the COVID-19 pandemic, studies typically reported a relatively higher risk of infection in adults than in younger persons [6-8], and a higher risk of infection in school-aged children (6-14 years) than in child-care and kindergarten (0-5 years) [9]. Subsequent seroprevalence studies, however, have suggested that COVID-19 infections in younger persons may have been underreported due to children and adolescents being largely asymptomatic at a time when testing capacity was low [10, 11]. On the other hand, reduced levels of transmission may have contributed to less infection in younger people during the first two wild-type dominated waves of the pandemic [12-14]. Data from the Corona-KiTa report, published by the RKI and German Youth Institute (DJI), also shows that during the first two infection waves, the incidence of disease in child and adolescent populations, particularly those aged 0-5, was not only lower, but that the timing of the infection wave for this specific age group rose after and declined before older populations [9].

Contact tracing and vaccination as infection control measures

Infection control measures are specific actions taken to stop or reduce the spread of disease so as to reduce associated morbidity, mortality, and the overburdening of health-care systems. Within Germany during the COVID-19 pandemic, such measures were defined at the federal and state level, and implemented by district health authorities. In addition to the use of contact tracing and vaccination as critical control measures throughout the pandemic, other measures included: periods of lockdown, travel restrictions and nightly curfews; temporary closure of schools, businesses and religious institutions; prohibition of social, cultural and sporting events; personal hygiene measures (e.g., handwashing and sanitization); limitations on social contacts and physical distancing (1.5m radius); and case isolation [15].

Most infection control measures were applied broadly to the entire population, including and often focused on young people, due to concerns about serious outcomes [16-21] including "Long-COVID" [22] and transmission into high-risk groups based on social contact data [23-26]. While understood to be overall effective, restrictive infection control measures were associated with increased levels of stress [27], language problems, weight gain [28], anxiety [29], stigmatization [30], depression [31], reduced sleep quality [9, 28, 32], and reduced intelligence test results [33]. Particularly in children and young people, the proportion of individuals with mental health problems dramatically increased during the pandemic [31, 34, 35]. Young people were also shown to have decreased social and physical activity [32] paired with increased media consumption [36], overweight and obesity [37-39]. Further studies showed decreases in language development and fine motor skills in children [28]. Amongst adults and the elderly, studies have reported an increase in economic difficulty, such as loss of income or savings, and reduced access to health and other essential services [32]. For parents of young children, limited access to child-care facilities was found to be an important co-factor for increased stress and anxiety [9]. Increases in all forms of domestic violence, including sexual violence, have been reported [40, 41] amid concerns that prolonged confinement might be a risk factor for increased family conflicts and child mistreatment [15, 42]. German authorities monitored many of the negative impacts of infection control measures, particularly on children and adolescents' education, fitness, social adjustment and mental health [15, 43].

Contact tracing and quarantine are specific infection control measures involving the identification and isolation of individuals who have been in close contact with someone diagnosed with a transmissible disease, which is distinct from the isolation of a known or confirmed case. Unlike many countries, Germany's well defined infection surveillance processes [44, 45], was shown to have detected and reported close to the true number of COVID-19 cases during the pandemic [46, 47] through a broad range of measures including: disease education campaigns and daily status updates to heighten awareness of periods of intensified infectivity; automated contact tracing solutions, such as the Corona Warn App, which detected and notified users of their proximity to a known infection; event check-in systems, including mobile apps (e.g., Luca-app), to identify potential disease transmission; and subsidised home testing and ubiquitous free antigen and PCR testing sites that made it easy for people to know their infection status. While antigen test results were not used for reporting or contact tracing activities during the pandemic, a positive result from an antigen test was generally the pre-cursor for subsequent PCR testing, thereby increasing the detection of confirmed cases in the community and quarantined populations.

Laboratories were required, as per the Infectious Disease Protection Act (Infektionsschutzgesetz, § 7 to 9 IfSG) to report each confirmed case to local health authorities. Specially trained contact tracing staff then attempted to contact and conduct telephone interviews with all COVID-19 cases to identify close contacts, also known as contact persons, while informing people of their legal requirement to isolate and collecting additional medical information. If the health authority was unable to establish contact with a known case, the local regulatory authority was informed, and an officer was dispatched to establish contact with the case. Ultimately, the RNK/HD Health Authority estimates that during the period of active contact tracing, it was able to establish contact with 85% of COVID-19 cases, plus an additional 5% through the local regulatory authority. Additional contact tracing measures by specialist teams were taken to protect elderly people in care facilities, and young people in kindergartens and schools. Once identified, close contacts were contacted by contact tracing staff and informed of their legal obligation to quarantine themselves within their residence, in a separate room away from other co-inhabitants, for a period of between 5 to 14 days. The precise definition of close contact and duration of quarantine were specified and updated throughout the pandemic by state governments in accord with national RKI guidelines [48]. To ensure compliance, officers of the local regulatory authority investigated reports of potential breaches and undertook spot inspections of disease case isolations and quarantined individuals. While rarely issued in RNK/HD, regulatory officers were empowered to issue fines of up to €25,000 or 5 years in prison in extreme circumstances with the potential to cause harm to others (§ 74, 75 IFSG).

Vaccines to prevent the spread and minimise the impact of COVID-19 were approved for emergency use in Germany, following recommendations by the European Medicines Agency (EMA), on 21

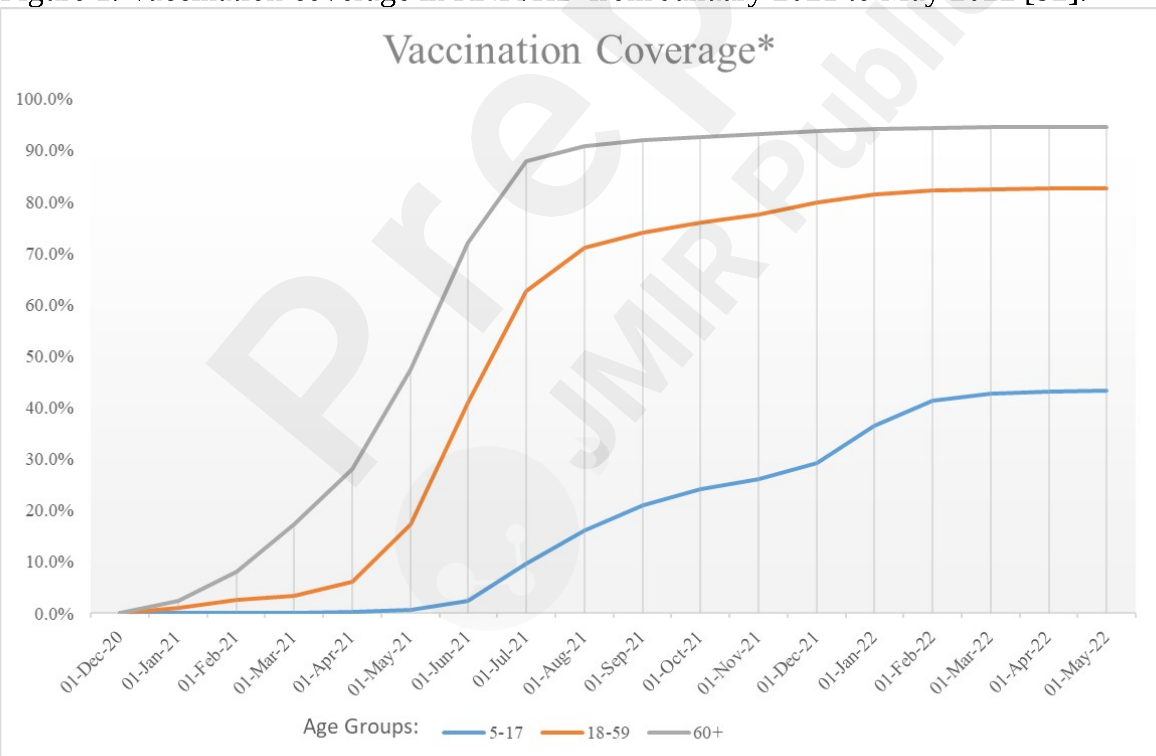
December 2020 (Table 1). The RNK/HD Health Authority subsequently administered the first doses in the district on 27 December 2020 [49].

Table 1: COVID-19 vaccine approvals

Registered name	Manufacture	Technology	Approval date
Comirnaty	BioNTech/Pfizer	mRNA	21 December 2020
Spikevax	Moderna	mRNA	6 January 2021
Vaxzevria	Oxford/AstraZeneca	Adenovirus vector	29th January 2021
Ad26.COV2.S	Janssen (Johnson & Johnson)	Adenovirus vector	11 March 2021
Nuvaxovid	Novavax	NVX-CoV2373	20 December 2021

As part of a national strategy targeting limited supply to elderly and high-risk individuals [49], the RNK/HD Health Authority initially administered vaccinations through three immunisation centres in the RNK/HD district and mobile teams that focused on aged care facilities and other vulnerable groups. Vaccines were made more broadly available through medical practices from 7 April 2021, and later in pharmacies from 8th February 2022. Prioritized distribution of the vaccine ended, and young people over the age of 12 were granted access (despite no recommendation from the national vaccine advisory authority – STIKO) following approval by the EMA [50], on 7th June 2021 [51]. While vaccines were a mandatory requirement for people working in medical or aged care facilities, the general population was encouraged to vaccinate themselves through social responsibility education programs and incentive schemes.

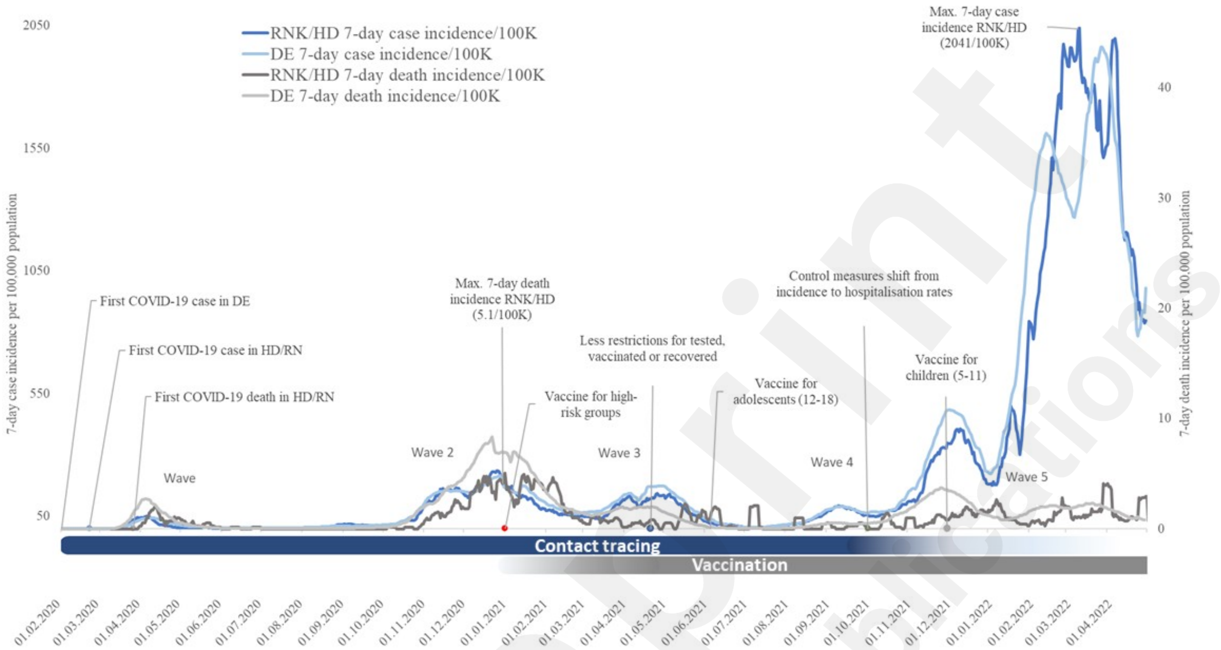
Figure 1. Vaccination coverage in RNK/HD from January 2021 to May 2022 [52].



* Vaccination coverage = minimum 2 doses.

Contact tracing efforts and quarantine in RNK/HD were reduced following the wide-spread adoption of the COVID-19 vaccine towards the end of 2021. By this time, many of the other infection control measures limiting social contact had been lifted for people who could demonstrate a negative test result, vaccination, or infection within the last 90 days. As case fatalities remained relatively low following the omicron dominated fifth phase, and the capacity of hospitals and intensive care units were no longer critical in 2022, most institutions and businesses gradually returned to normal operation in adherence with other infection control measures. At the end of March 2022, the RNK/HD Health Authority ceased active contact tracing, and on 15 November 2022, the state government of Baden-Wuerttemberg lifted the legal requirement to quarantine (Figure 2).

Figure 2: Timeline of contact tracing and vaccination in the context of COVID-19 disease incidence (morbidity) and death (mortality) in RNK/HD and Germany (DE).

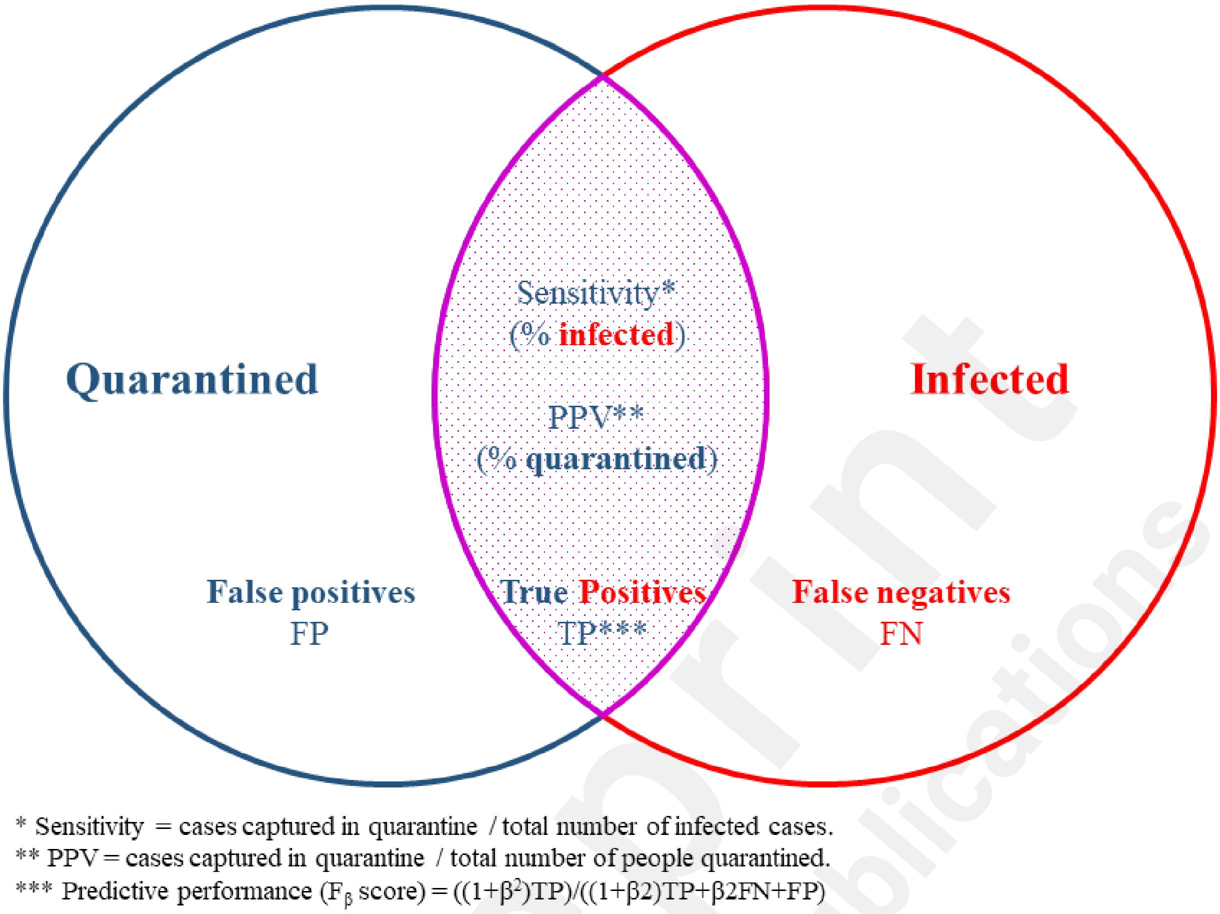


Measuring contact tracing effectiveness and efficiency

A Cochrane rapid review on quarantine during the COVID-19 pandemic concluded that while broadly accepted as effective, there is an apparent lack of agreed metrics and data to demonstrate its effectiveness [53]. This conclusion was supported by a subsequent systematic review of observational and modelling studies of COVID-19 reports, which itself concluded that the spread of the disease could be stopped if at least 80% of cases were captured in quarantine, or could be slowed at levels below 80% [54].

This paper examines the use of quarantine as an infection control measure in RNK/HD following initial disease outbreak until the introduction of the vaccine. To assess overall effectiveness in a real life setting, we propose the use of quarantine sensitivity, as the proportion of the infected population captured in quarantine (Figure 3). To assess overall efficiency, we propose the use of positive predictive value (PPV), as the proportion of quarantined population that tested positive while in quarantine. To assess the predictive performance, as a combined measure of sensitivity and PPV, we propose the use of an F_β score arbitrarily weighted to value sensitivity over PPV. Ideally, all infected people would be quarantined (sensitivity: 100%), and only infected people would be quarantined (PPV: 100%), resulting in a perfect predictive performance (F_β score: 1). In practice, quarantine may be considered to be overall effective if it captures enough of the infected population to limit or reduce disease spread, and efficient if the number of healthy people place in quarantine can be limited to what is considered to be tolerable levels.

Figure 3. Quarantine sensitivity, positive predictive value (PPV) and predictive performance (F_β score).



Study objectives

The study focuses on contact tracing and the use of quarantine within three distinct age groups during the initial five phases of the COVID-19 pandemic. In particular, did the use of quarantine reflect variations in COVID-19 infection and mortality that might exist between the different groups and at different time points? Was contact tracing effective in identifying and capturing potentially infected individuals in quarantine; how efficient was contact tracing in capturing only infected individuals in quarantine; and were there differences between age groups and between the different phases of the pandemic?

Methods

Data collection and storage

All known COVID-19 cases, including the first cases in RNK on 27 February 2020, and Heidelberg on 28 February 2020, were reported within 24 hours to district health authorities. The RNK/HD District Health Authority then transmitted case data to the RKI while managing the process of infectious disease control. Initial measures, focused on containment, were managed largely via ad hoc systems until a dedicated COVID-19 monitoring and containment system, including an operational database, was developed and initiated on 8 March 2020. A database for research purposes was subsequently constructed from comprehensive outputs (csv files) of the operational database, archived for each day until November 2022.

Until August 2021 (end of the third phase), the RNK/HD Health Authority contacted each confirmed case via telephone and regular mail to inform them of their legal obligation to isolate, collect medical information and identify potentially infected contact persons. RNK/HD contact tracing staff received special training and used a standardized procedure to collect and document case details for national reporting, contact tracing and other operational purposes.

This study includes data from the first documented infection, 27 February 2020, until the phasing out of contact tracing in the region, 30 April 2022. Medical records collected by the RNK/HD Health Authority without informed consent were anonymised, aggregated and analysed according to EU General Data Protection Regulations (GDPR 2016/679) , recitals 1, 4, 26 and 159 [55], and the Treaty on the Functioning of the European Union, Title XIX, Research and Technological Development Space, Article 179 [56]. The use of patient data records by health authority staff without informed consent was approved for use in this study by the University of Heidelberg, Medical Faculty Ethics Committee on 30 September 2022 (ref.: S-488/2022).

Additional national COVID-19 data and statistics, including vaccination levels, accessed 31 May 2022, were obtained from the RKI national database, accessed 1 February 2023, and other publicly released information [4]. Population data, valid for 31.12.2020, for RNK/HD was obtained from the webpage of the Baden-Württemberg Office for Statistics, accessed 6 October 2022 [57].

Documentation and outcomes

For reporting purposes, a confirmed COVID-19 case was defined as someone with a positive SARS-CoV-2 reverse transcription polymerase chain reaction (RT-PCR) test regardless of symptoms [58]. People in close contact with a confirmed case, required by law to undergo quarantine, were contacted separately and documented as non-cases within the COVID-19 monitoring and containment system. A death was documented as COVID-19 related if a person tested positive for COVID-19 via RT-PCR before or immediately after death, and where COVID-19 was assessed by medical professionals to have contributed to or caused the death.

Within the research database, a confirmed case was documented with the date of disease onset as the documented date of testing (>90% of records), or when a positive PCR result was first documented if no actual test date was documented in the operational database. Contact persons were documented as non-confirmed cases with a quarantine start date when first entered in the operational database, and an end date based on the median duration of quarantine for each specific day during the study period. Infected contact persons were identified where the date of disease onset occurred within the period of quarantine. Non-infected contact persons were those who were not infected during the quarantine period (but may have been infected at another time). To avoid double counting across study phases, records of infected contact persons who were quarantined in one study phase, but may have tested positive and/or died in another study phase, were included only in the phase where individuals were quarantined. Similarly for non-quarantined persons, if a death occurred in a subsequent study phase to the infection, the record was included only once, in the phase of the infection.

Statistical analysis

This publication presents data collected by the RNK/HD Health Authority, the sixth largest district health authority in Germany, covering a combined population of 706,974 registered residents as of 31 December 2020 [57].

Data was included from the first case in the RNK/HD area, recorded 27 February 2020, until 30

April 2022, by which time many of the infection control measures, including contact tracing, were relaxed. The study timeframe was separated into five phases (Table 2), each phase starting at the beginning of a calendar week in which incidence rates increased due to a new virus variant or following a summer lull in infection levels, as per RKI retrospective classification [5]. Lulls are included at the end of a phase because quarantine, infections and deaths, as well as emerging virus variants were more often initiated during infection waves extending into lulls rather than during lulls extending into waves.

Table 2. Initial 5 phases of the COVID-19 pandemic in Germany [5].

Study phase	From – To	RKI phase description	Dominant Viral Strain
1	27.02.2020 - 27.09.2020	Sporadic cases	Wild-type
		First wave	Wild-type
		Summer lull	Wild-type
2	28.09.2020 - 28.02.2021	Second wave	Wild-type
3	01.03.2021 - 01.08.2021	Third wave	Alpha
		Summer lull	Alpha
4	02.08.2021 - 26.12.2021	Fourth wave	Delta
5	27.12.2021-30.04.2022	Sixth wave	Omicron

Data was further categorized in three age groups:

- Young people, predominantly those attending kindergarten and school, aged 0-19 years (N=130,387);
- Adults, predominantly higher education students, parents, and those engaged in the workforce (retirement age in Germany: 65), aged 20-65 years (N=437,581); and
- Elderly, predominantly retired persons, including people in aged care facilities, and those at high-risk of hospitalization and a fatal outcome from COVID-19 [59], aged 66 years and above (N=139,006).

The risks of COVID-19 related quarantine, infection, and death were each calculated as the number of individuals quarantined, infected or who died with or of COVID-19 during the specified time period divided by the relevant sub-population on 31 December 2020 [57]. All risk calculations consider single instances during the specified time, and exclude additional instances where an individual may have been quarantined or infected multiple times. Re-infections and/or multiple quarantine events were counted as separate events. The adult age group, as the largest sub-population (61.9%), was used as reference group to calculate the relative risk (RR), assuming normal distribution, and corresponding 95% confidence interval (95%CI) calculated using a Wald test with bivariable logistic regression.

Using a contingency table to evaluate binary classifiers (Table 3), the sensitivity of contact tracing or quarantine decisions was calculated as the percentage of COVID-19 cases captured in quarantine (True positives(TP)/(TP + False negatives(FN)). The positive predictive value (PPV) of quarantine was calculated as the percentage of persons quarantined who tested positive for COVID-19 during the quarantine period (TP/(TP + FP)). As a combined measure of predicitive performance, F_β scores were weighted towards sensitivity rather than PPV (β=2), and calculated as the weighted product of PPV and sensitivity, divided by weighted PPV plus sensitivity (simplified to: $((1+\beta^2)TP)/((1+\beta 2)TP+\beta 2FN+FP))$. Test accuracy was not possible to calculate because the number of true negatives (contacts, but not close contracts, of infected persons) was not documented.

Table 3: Contingency table for evaluating quarantine sensitivity, PPV and predictive performance.*

		Quarantined		Sensitivity	PPV	F_β score
		+	-			
Infected	+	TP	FN	TP/(TP+FN)	TP/(TP+FP)	$((1+\beta^2)TP)/((1+\beta^2)TP+\beta^2FN+FP)$
	-	FP				

* TP: True positives; FN: False negatives; FP: False positives

Records without birthdates, or implausible birthdates, were excluded from age related analyses (988 or 1.25% quarantine records and 34 or 0.017% case records).

To validate results, supplementary risk analyses of infection, quarantine or death were done grouping data by gender and location (Heidelberg city Vs surrounding RNK district). No significant differences were expected between males and females, with some potential differences between RNK and HD due to demographical variations.

In this report, comparable output values ranging between 0.001 and 999 were rounded to three meaningful digits (e.g., 12.3, 1.23, 0.123, 0.012, and 0.001). A zero decimal was added to a natural number to indicate that rounding has occurred (e.g., 12.0, 1.20).

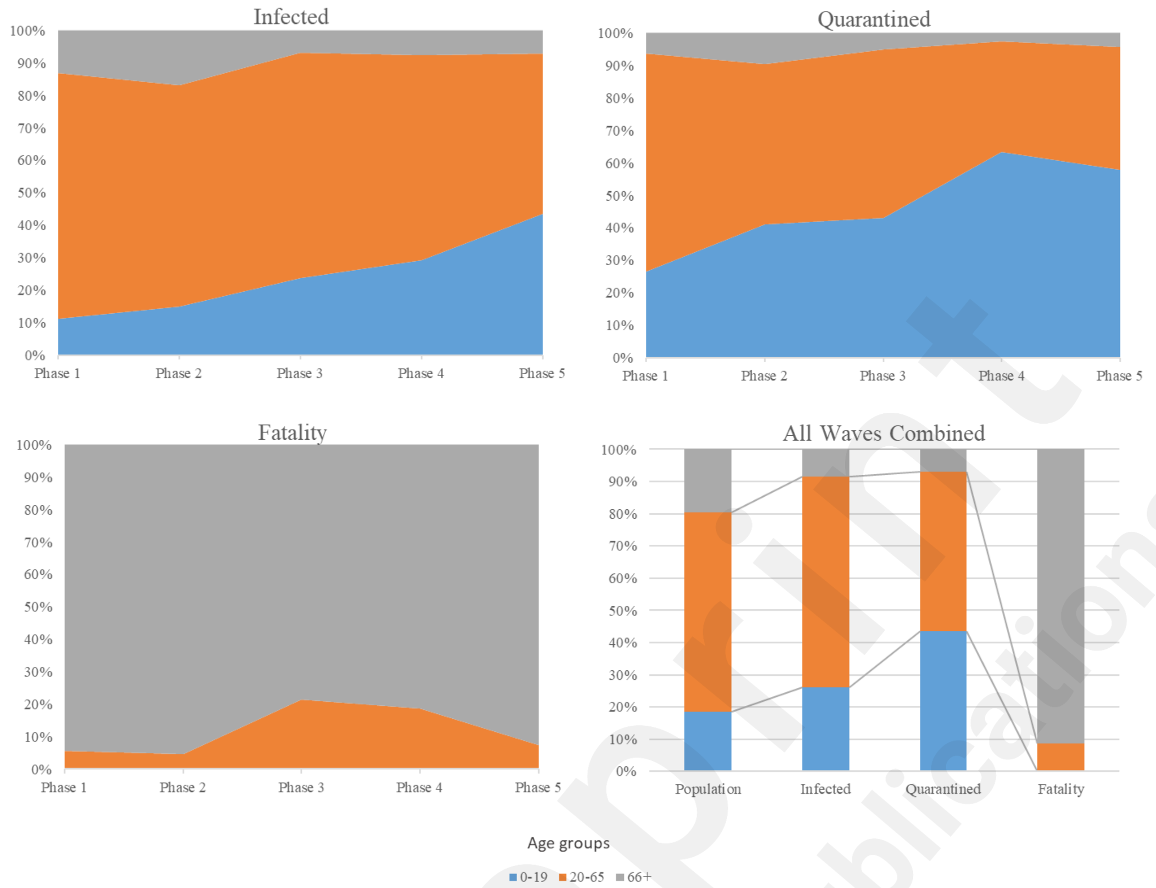
Data processing and analysis in this report were undertaken using MS-SQL and python version 3.12 [60], with all statistical assessments performed using pandas version 2.1.1 [61], statsmodels version 0.14.0 [62], scipy version 1.11.3 [63], matplotlib version 3.8.4 and matplotlib-venn version 0.11.10 [64]. Additional graphs and graphical tables were prepared using MS Excel 2016 [65].

Results

Age group proportion of infection, quarantine and case fatalities

Initially, during the first two phases of the pandemic, young people aged 0-19 were under-represented within the SARS-CoV-2 infected population (11.2% and 15.0% of confirmed cases, relative to 18.4% of the local population; Figure 4; Supplementary Table 5). Ultimately however, over five phases of the pandemic, young people were over-represented within the infected population, accounting for 26.1% of COVID-19 infections. Adults aged 20-65 were marginally over-represented within the infected population (65.5% of cases relative to 61.9% of the population), particularly in the first phase of the pandemic (75.7% of COVID-19 infections). By contrast, elderly people, aged over 65, were under-represented within the infected population (8.46% of cases and 19.7% of the local population).

Figure 4: Proportion of COVID-19 related infections, quarantine and death cases, by age group and pandemic phase (stacked areas) from 27 January 2020 until 30 April 2022.



Young people were over-represented within the quarantined population (43.5% of the total quarantined population relative to 18.4% of the local population; Figure 4; Supplementary Table 5), increasing from 26.6% in the first phase to a maximum of 63.4% in the fourth phase. Adults and the elderly were both under-represented within the quarantine population (adults 49.5% and the elderly 7.07% of cases, and 61.9% and 19.7% of the total population respectively), particularly in the fourth study phase (34.1% and 2.44% of cases respectively).

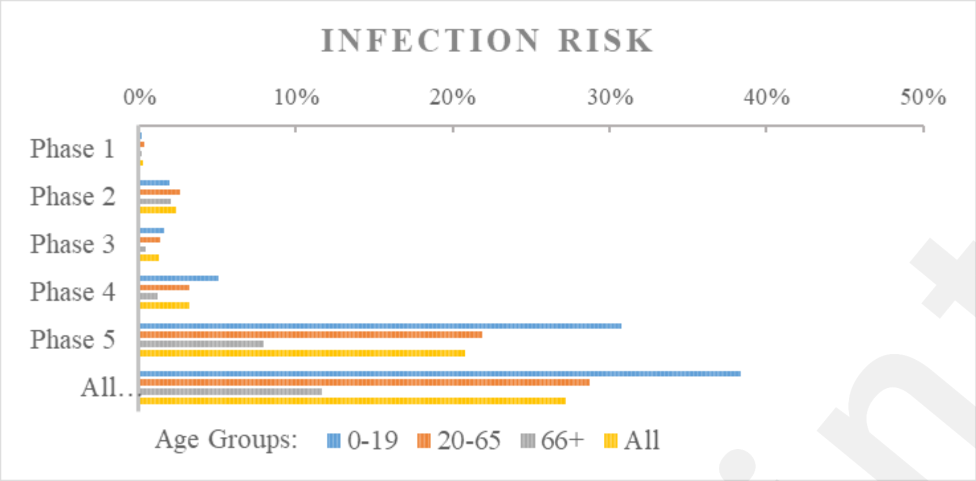
The vast majority of COVID-19 associated deaths documented by the RNK/HD Health Authority occurred within the elderly population, aged over 65 (91.4% of COVID-19 deaths across all study phases; Figure 4; Supplementary Table 5). All remaining deaths occurred in adults aged 20-65 (8.58%), with no deaths in younger people aged 0-19. During the third and fourth phases, adults accounted for relatively greater proportions of the COVID-19 deaths (21.5% and 18.6%) compared to the first, second and fifth phases (5.66%, 4.69% and 7.32%, respectively).

Risks of infection, quarantine, mortality and case fatality

Within the RNK/HD area, 198,148 SARS-CoV-2 infections were documented during the study period (Supplementary Table 6) . The lowest risk of infection (0.295%) occurred in the first phase of the pandemic, during which 0.181% of young persons, 0.361% of adults and 0.196% of elderly people were identified as having been infected (Figure 5; Supplementary Table 5). The greatest risk of infection (20.8%) was in the omicron-dominated fifth phase, during which 31.0% of young persons, 22.0% of adults and 7.98% of elderly people were identified as having been infected.

During the period of active contact tracing (phases 1-3) in RNK/HD, the risk of infection for all age groups was highest in study phase 2 of the pandemic.

Figure 5. Age group risk of infection during initial 5 phases of the COVID-19 pandemic.



For each of the age groups, the lowest risk of infection occurred in the first phase of the pandemic, and the greatest risks occurred in the fifth phase (Figure 5). During the first two phases of the pandemic, the risk of infection was lower for young people compared to adults (RR: 0.502 phase 1 and 0.745 phase 2; Supplementary Table 7), but higher than adults across all phases (RR: 1.35; 95%CI 1.34-1.36). Elderly people maintained a significantly lower risk of infection than adults throughout the first five phases of the pandemic (all phases RR: 0.401; 95% CI: 0.395-0.407).

Just over one in ten people within RNK/HD were placed in quarantine during the study period (risk: 10.4%). The greatest risk of being quarantined in the RNK/HD district occurred in the second phase of the pandemic (5.32%; Figure 6; Supplementary Table 7). The ratio of quarantine events to confirmed cases was highest in phase 1; decreasing in each successive phase of the pandemic from 4.10 in phase 1 to 0.036 in phase 5; and highest for young people (ranging from 8.97 to 0.077; Figure 7). Elderly people had the lowest ratio of quarantine events to confirmed cases during all phases of the pandemic (ranging from 1.78 to 0.020). Just over one in four young people were placed in quarantine (risk: 25.9%), compared to one in ten adults (risk: 8.81%) and one in twenty-five elderly people (risk: 3.84%). Young people had close to three times the risk of being placed in quarantine than adults (RR: 2.94; 95% CI: 2.90-2.98), while elderly people had less than half the risk of quarantine than adults (RR: 0.436; 95% CI: 0.424-0.448).

Figure 6: Age group risk of quarantine during initial 5 phases of the COVID-19 pandemic.

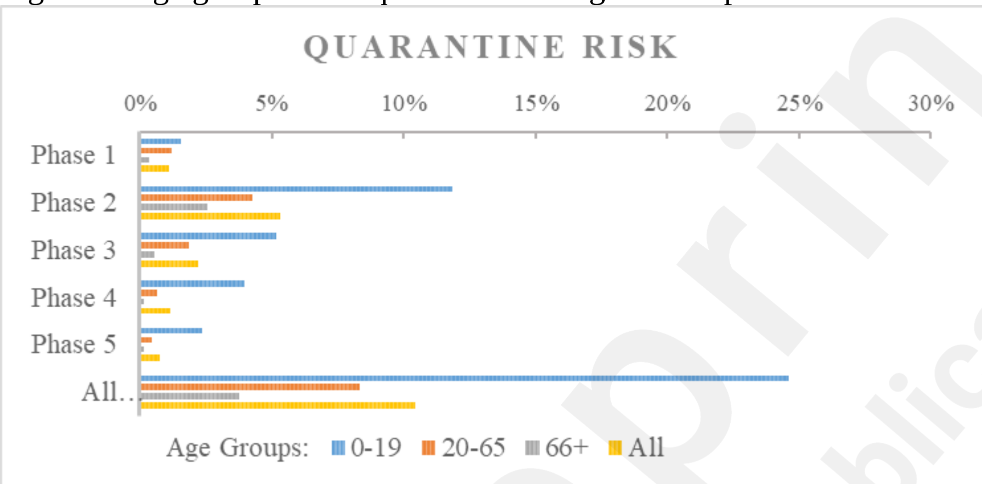
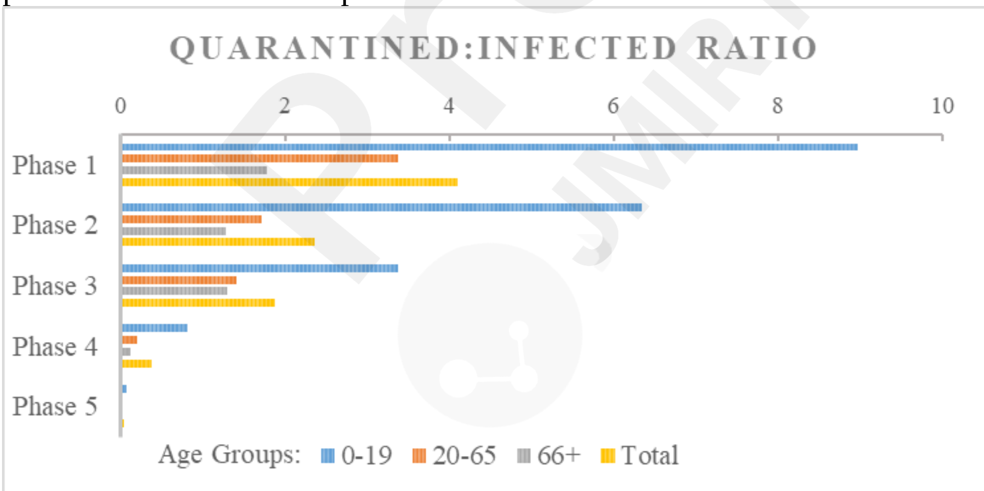


Figure 7: Ratio of individuals placed in quarantine to confirmed infection cases during initial 5 phases of the COVID-19 pandemic.



The risk of death following infection (case fatality) was 0.485% during the study period, decreasing during each successive phase from 2.54% in phase 1 to 0.139% in phase 5 (Figure 8; Supplementary Table 7). Within the elderly population, the case fatality risk reduced from 18.3% in phase 1 to 1.72% in phase 5. The overall risk of death (mortality) in HD/RNK during the study period was 0.132% (0.613% of elderly people), peaking in the second phase of the pandemic (all age groups: 0.066%; elderly people: 0.322%;Figure 9). Elderly people had between 11.5 and 64.0 times higher risk of COVID-19 mortality than adults, with the lowest relative risk in the third phase of the pandemic following the targeted release of the vaccine to elderly and high risk individuals.

Figure 8: Age group risk of death following COVID-19 infection (case fatality) during initial 5 phases of the pandemic.

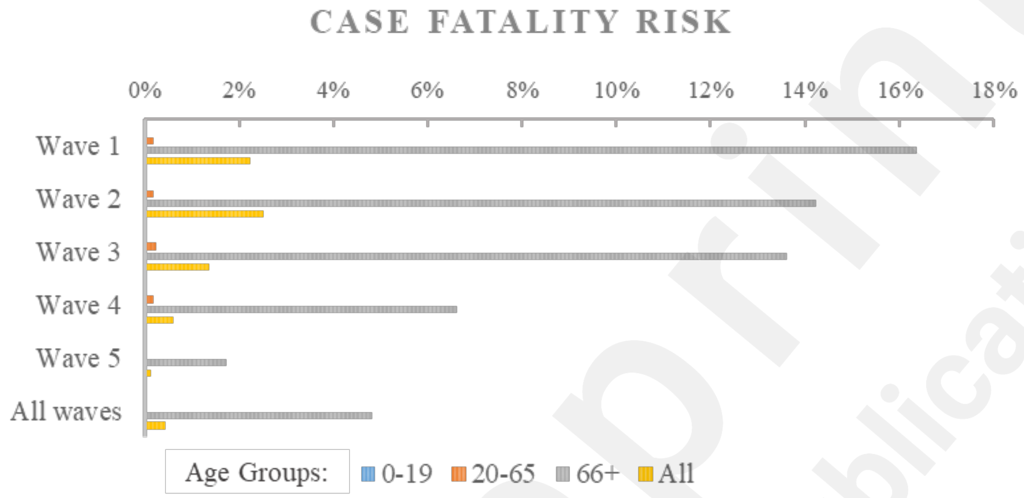
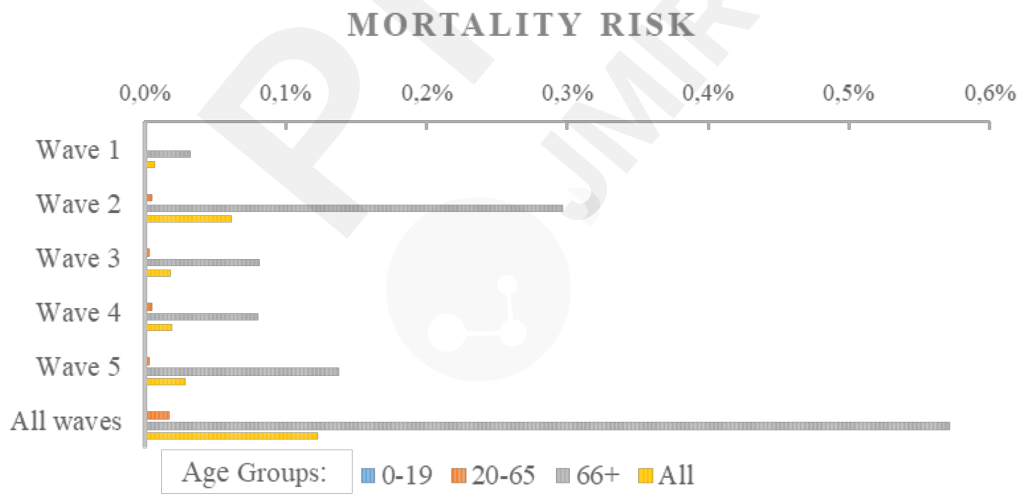


Figure 9: Age group risk of death with COVID-19 (mortality) during initial 5 phases of the pandemic.



Supplementary analyses, intended to validate results, revealed no apparent difference between males and females for infection (male risk: 27.5%; female risk: 28.3%; RR female relative to male: 1.03; 95%CI: 1.02-1.04), quarantine (male risk: 10.6%; female risk: 11.0%; RR female relative to male: 1.04; 95%CI: 1.03-1.06) or death (male risk: 0.129%; female risk: 0.133%; RR female to male: 1.03; 95%CI: 0.903-1.17; Supplementary Table 8). Compared to those living in Heidelberg, people living the surrounding RNK district had slightly higher risks of infection (risk: 28.3%; RR to HD: 1.15; 95%CI: 1.14-1.16), quarantine (risk: 11.4%; RR to HD: 1.26; 95%CI: 1.24-1.29) and death (risk: 0.141%; RR to HD: 1.55; 95%CI: 1.30-1.85).

An additional analysis of RNK/HD data confirmed results from the RKI Corona-KiTa study [9] showing that the risk of infection in young children (aged 0-5) in particular remained below the risk of infection in adults in each of phase of the pandemic until 30 April 2022 (Supplementary Table 10). Despite a lower risk of infection than adults, and no associated deaths, young children aged 0-5 had the highest risk of being placed in quarantine (risk: 28.5%; RR to adults: 3.23; 95% CI: 3.18-3.29).

Quarantine sensitivity, positive predictive value and predictive performance

The size of the quarantine population was larger than the size of the infected population during the first three phases of the pandemic, with increasing overlap, particularly for young people, between the two populations (sensitivity, PPV and predictive performance;
Figure 10). During the first phase of the pandemic, around 1/5th of all cases in RNK/HD were captured in quarantine (sensitivity: 19.2%%); Table 4), and only 1 in 20 quarantined people tested positive in quarantine (PPV: 4.69%). Taken together, this resulted in a low predictive performance (β-weighted (2) F_β score: 0.119). During phases 2 and 3 of the pandemic, sensitivity increased to 34.6 and 39.7% and PPV increased to 14.2 and 21.2%, and F_β scores improved to 0.272 and 0.338 respectively. As contact tracing efforts were scaled back in phases 4 and 5, sensitivity decreased progressively to 9.83% and 0.693% respectively). PPV, on the other hand, continued to increase and peaked in phase 4 (25.9%) before reducing in phase 5 (19.0%). Predictive performance (F_β score weighted towards sensitivity – β=2) reduced in both the fourth (0.112) and fifth (0.009) phases.

Figure 10. Proportional Venn diagrams of COVID-19 infections captured in quarantine (sensitivity) and within quarantined population (PPV) providing elements for predictive performance (F-score) calculations in age groups and phases of the pandemic.

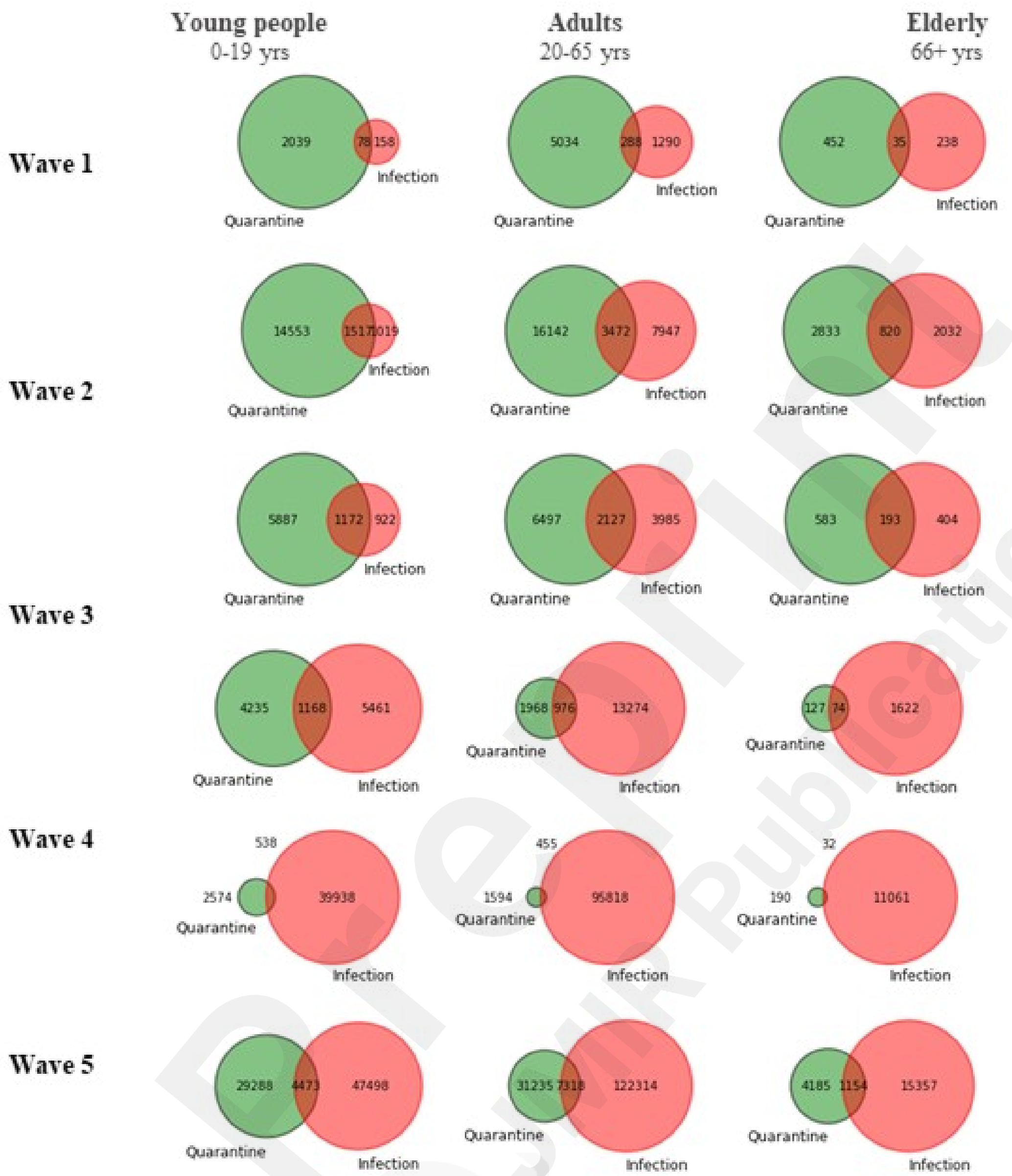


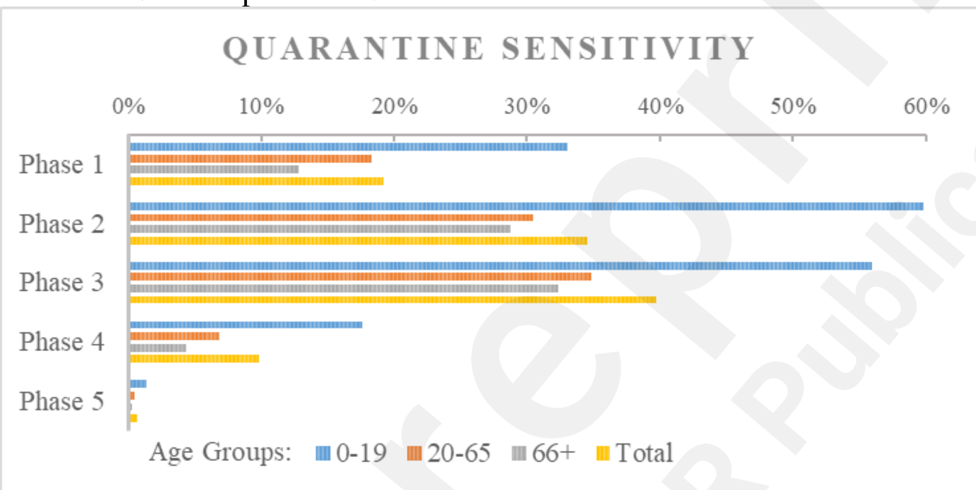
Table 4: Infection and quarantine contingency tables with quarantine sensitivity, PPV and F_β score.

		Quarantined		Sensitivity	PPV	F_β score
		+	-			
Infected	+	TP	FN	TP/ (TP+FN)	TP/ (TP+FP)	$((1+\beta^2)TP)/((1+\beta^2)TP+\beta^2FN+FP)$
	-	FP	TN			
Phase 1	+	401	1,686	19.2%	4.69%	0.119
	-	8,149				
Phase 2	+	5,810	11,004	34.6%	14.6%	0.272
	-	33,877				
Phase 3	+	3,492	5,311	39.7%	21.2%	0.338
	-	12,970				

Phase 4	+	2,219	20,359	9.8%	25.9%	0.112
	-	6,336				
Phase 5	+	1,025	146,841	0.7%	19.0%	0.009
	-	4,362				

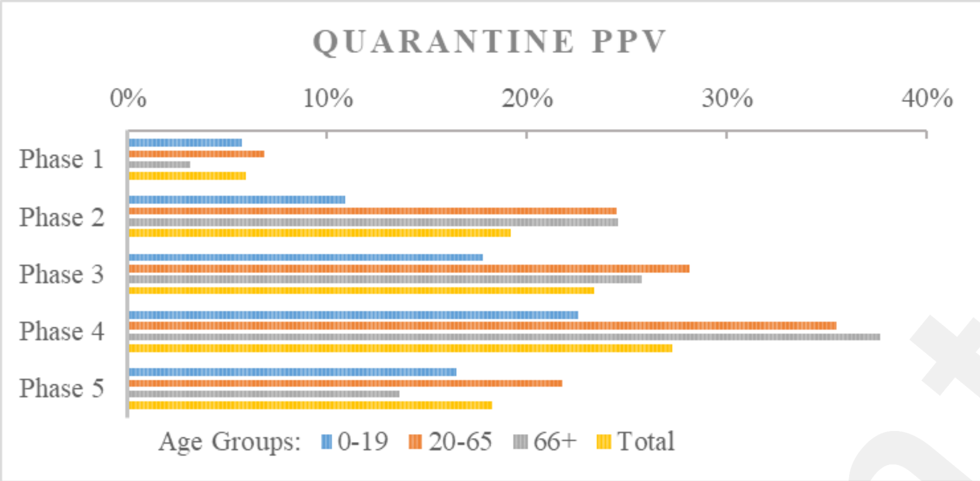
Comparing age groups during the period of active contact tracing (phases 1-3), quarantine sensitivity was highest in the younger population, increasing from around a third in phase 1 (33.1%) to nearly two thirds in phases 2 and 3 (59.8% and 56.0% respectively; Figure 11; Supplementary Table 9). Quarantine sensitivity for adults and the elderly started at around 1/10th in phase 1 (adults: 12.8; elderly: 8.36), increasing to almost a third in phase 3 (adults: 34.8%; elderly: 32.3%). Contact tracing sensitivity was lowest for elderly people in each study phase. As contact tracing efforts were reduced in phases 4 and 5, sensitivity reduced for all age groups (young: 17.6% to 1.33%; adults: 6.85% to 0.473%; elderly people: 4.36% to 0.288%).

Figure 11. Age group quarantine sensitivity (% cases captured in quarantine) during the first 5 phases of the COVID-19 pandemic.



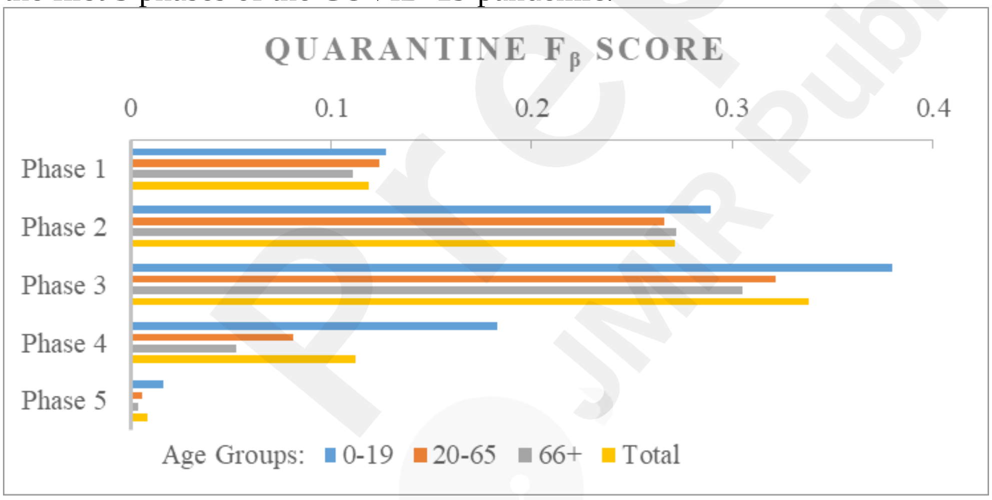
Comparing the PPV within different age groups, greater proportions of adults and the elderly in quarantine tested positive, compared to younger persons in almost each of the study phases (Figure 12). In phase 4, when PPV was highest, 36.8% of elderly people placed in quarantine tested positive, 33.2% of adults tested positive and 21.6% of young people tested positive (Supplimentary Table 8). In phase 3, during the period of active contact tracing, 24.9% of elderly people in quarantine tested positive, 24.7% of adults tested positive and 16.6% of young people tested positive.

Figure 12: Age group quarantine PPV (% quarantine population infected) during the first 5 phases of the COVID-19 pandemic.



The predictive performance of contact tracing (F_β weighted towards sensitivity, β=2) increased during the first three phases of the pandemic and decreased rapidly in the fourth and fifth phases as contact tracing efforts were reduced (F_β scores, phases 1-5 respectively: 0.119, 0.272, 0.338, 0.112, 0.009; Figure 13; Supplementary Table 8). The predictive performance of contract tracing was higher for young people than other age groups for each of the study phases, reaching a maximum of 0.380 in phase 3.

Figure 13: Age group quarantine predictive performance (β=2, weighted towards sensitivity) during the first 5 phases of the COVID-19 pandemic.



Discussion

Data of SAR-CoV-2 infections and case fatalities from the RNK/HD Health Authority is consistent with national statistics with regard to scale [3, 36] and the timing of infection waves and lull periods [5]. The risks of infection, quarantine and case fatality vary significantly between age groups, with young people having the highest risks of infection and quarantine, while mortality and case fatalities were limited largely to the elderly population.

The overall effectiveness of contact tracing, considered to be the proportion of cases captured in quarantine (sensitivity), did not reach the level of 80%, which was predicted would stop further COVID-19 transmission. Nevertheless, sensitivity of around 40%, as demonstrated in the second and third phases of the pandemic, is likely to have contributed towards reduce transmission [54, 66, 67], thereby reducing severe and potentially fatal infections and the burden on health care systems. The overall efficiency of contact tracing, considered to be the proportion of quarantine cases that tested positive during quarantine (PPV) improved markedly throughout four of the five study phases, thereby reducing the burden on non-infected individuals. The $F_β$ score provides a single meaningful measurement of both the effectiveness and efficiency of contact tracing.

Variations in disease outcomes

Much of the variation in COVID-19 incidence and mortality reported in RNK/HD can be attributed to the targeted release of the vaccine to elderly people and changes in the infectivity of virus variants [68, 69]. Initially, when limited supplies of the vaccine were targeted to high risk adults and elderly people, there was a reduced the risk of death in the elderly group (both mortality and case fatality). At the same time, however, the increased proportion of deaths in the adult group suggests a failure of the vaccine targeting to reach high-risk individuals in this age group (those with pre-existing diabetes, obesity, heart failure, lung disease or dementia). Elderly people have been shown to be more likely to engage in disease preventative behaviours compared to people in other age groups, both in general [70, 71] and during the COVID-19 pandemic [72], which may also have contributed to better outcomes in this group.

Consistent with other published research**,** data from RNK/HD shows that relatively fewer infections were reported in young people compared with adults or elderly during the first two phases of the pandemic [2, 6-9]. On one hand, this may be due to a lack of testing within this group [10, 11]. Alternatively, recent data from human challenge experiments suggests a strong correlation between symptoms and wild-type disease transmission [12], which supports data from other studies showing that the initial contagion spread predominantly within the adult population where the disease was initially established [9, 23]. Data from the German RKI Corona-KiTa study also shows that the risk of infection in young children aged 0-5 was lower than in other age groups during the initial phases of the pandemic [9]. An additional sub-analysis of data from RNK/HD, confirmed that the risk of infection during the initial wild-type phases of the pandemic was lowest amongst young children aged 0-5.

Contact tracing and quarantine effectiveness and efficiency

Data from RNK/HD shows that quarantine sensitivity, PPV and $F_β$ score can be used as indicators of the overall effectiveness and efficiency of contact tracing efforts. Sensitivity provides a clear measurement of how effective contact tracing was in capturing the infected population in quarantine. To demonstrate that this success was not simply because more people were placed in quarantine, PPV (the proportion of the quarantined population who tested positive) provides a complimentary measurement of contact tracing efficiency. $F_β$ scores, weighted towards sensitivity ($β=2$), nevertheless, suggest that an optimum balance between effectiveness and efficiency was reached during the third phase of the pandemic with the highest $F_β$ score of 0.338 (when 39.7% of all infections were captured in quarantine and 21.2% of the quarantine population tested positive). Unweighted F-scores showed a similar pattern, but less reduction between phases 3 and 4 (Supplementary Table 11).

As a measure of overall effectiveness, quarantine sensitivity was low during the first study phase, presumably as systems were still being developed. Sensitivity then rose when the risks associated with COVID-19 infection were highest – capturing nearly half of all confirmed cases in the second phase of the pandemic. As contact tracing and quarantine were reduced in phases 4 and 5, and sensitivity reduced, other infection control measures, such as freely available antigen and PCR testing, continued to help people know when to self-isolate following an infection, and to self-quarantine following contact with an infected person.

As a measure of overall efficiency, PPV increased from around 5-27% during the first four phases of the pandemic as free PCR testing was made increasingly available, and other policy and operational practices were fine tuned. Policies to exempt fully vaccinated people from quarantine may also have contributed to the improvement of PPV, although PPV did improve for young people despite limited vaccine availability in phases 3 and 4. Other more complex factors, such as the experience and expertise of contact tracing staff and policy makers, may also have contributed to the increasing proportion of infections in the quarantine population.

As a combined measure of predictive performance, weighted to value sensitivity over PPV, increasing F_β scores reflect both simultaneous expansion and improvement of contact tracing processes during the first three phases of the pandemic. Conversely, decreasing F_β score during phases 4 and 5 reflect the curtailment of contact tracing efforts, which particularly affected sensitivity. By factoring in both sensitivity and PPV, F_β scores provide a single measure to describe the overall efficiency and effectiveness of contact tracing measures.

Higher levels of quarantine sensitivity, but lower PPV and F_β scores for young people compared to adults and the elderly highlight the disproportionate application of quarantined between the groups. The reason why a lot of young people were quarantine has been suggested to be a result of children having more social contacts, such as in a classroom or kindergarten situation [26]. For small children, the conditions of quarantine were at times less specific due to practical reasons, such as the exemption from mask usage, and the difficulty in this age group to respect other hygiene and social distancing rules. On the other hand, school closures, and other restrictions were intended to reduce these sorts of social contacts during the initial phases of the COVID-19 pandemic [73]. As schools and kindergartens were opened, other hygiene and infection control measures were also intended to protect children from infection and avoid the need for wide-spread quarantine [74].

Quarantining young people

The intention to quarantine young people to prevent the transmission of disease into higher-risk groups was initially supported by contact pattern data suggesting that young people could be the source of transmission for broader outbreaks of influenza [25]. Transmission data from contact tracing studies, however, have meanwhile shown that SARS-CoV-2 transmission occurs predominantly within age groups, and unlike influenza, is more common within households and other settings than within schools [68, 75-77], which is supported by data from the RNK/HD area (manuscript in preparation). Data from the Corona-KiTa study also showed that infections in young adults, not children or adolescents, preceded each of the early phases of infection [9].

While the vaccine can be assumed to have reduced the risk of mortality and quarantine for the elderly population, this protective benefit does not appear to have influenced decisions to quarantine younger people. Higher levels of quarantine and the apparent need to capture a greater proportion of younger people in quarantine were initially supported by concerns for children themselves, including reports of unexpected pathology [16] and 'Long-COVID' [78]. These complications, however, were only anecdotally associated with children, and quickly identified to be of low incidence [14, 19, 22, 79-83]. Relatively little consideration was given to the reports of young people suffering the negative effects of quarantine [15, 28, 34, 35, 37-39, 42, 43], although it may have influenced decisions to keep schools and kindergartens open.

Limitations

As in other locations, failures to identify cases or under-reporting make it difficult to assert the true number of infections and deaths associated with COVID-19, which are expected to be higher than reported [84]. Many cases, particularly asymptomatic and mild ones were less likely to be tested, diagnosed and reported. This effect is likely to have been particularly relevant at the beginning of the pandemic when testing capacities were limited. Data collected for operational purposes can also be expected to contain more errors and exclusions (due to missing birthdate, for example), due to limited validation, than data collected solely and specifically for research purposes. While case reporting in Germany was reportedly high, quarantine sensitivity, PPV and F_β scores may still be affected by undetected cases in the community and within the quarantine population.

Measures of sensitivity, PPV and F_β scores reported in this paper do not consider any effect of a delay between testing and the notification of cases, nor the identification and notification of contact persons. Any delays between infection, case isolation and quarantine represents risks of disease transmission, and weakens the assumption that cases captured in quarantine (sensitivity) prevent all subsequent infections. To address this issue, delays would need to be quantified along with the likelihood of a resulting infection.

The size and nature of the domicile where people were quarantined may affect quarantine sensitivity, PPV and F_β scores. People living alone, for example, may be less likely to identify or infect contact persons than those living in large families or in a shared living arrangement, such as an aged care facility. Institutions where staff may be likely to enter and leave quarantine areas, and then have contact with other residents, in particular, may be particularly susceptible to disease transmission. Further research to establish the effect of living arrangements, such as occupant density and type of domicile, would be required to determine these effects.

The contribution of automated processes, such as mobile apps used to detect proximity to a known case, to the overall effectiveness or efficiency of contact tracing cannot be estimated or separated from contact tracing processes used by the RNK/HD Health Authority. A separate assessment of the quarantine sensitivity, PPV and F_β score of automated or digital solutions would be of value, allowing a comparison between different contact tracing methods.

Conclusions

During the first three phases of the pandemic, until August 2021, in the RNK/HD area, contact tracing was an important infection control measure, initially limiting the spread of SARS-CoV-2 and disease related fatalities. High levels of quarantine sensitivity and PPV at this time were sufficient to reduce virus transmission and avoid the overwhelming of the health system. Particularly in phases 2 and 3 of the pandemic, the availability of testing and iterative improvements in contact tracing processes meant that more of the infected population were captured in quarantine (sensitivity) and more of those quarantined were actually infected (PPV).

The impacts of COVID-19 in terms of infection, quarantine and death were heterogeneously distributed across different age groups. Even in phases where the incidence of infection in young people was lower than in adults, young people were significantly more likely to be placed in quarantine than adults. Despite being up to 56 times more likely to die following an infection than adults prior to the introduction of the vaccine, elderly people were significantly less likely to be placed in quarantine than adults or children. Urgent follow-up research is required to clarify, as has been suggested elsewhere, that transmission is predominantly within rather than between certain age groups.

In future disease outbreaks, an understanding of the COVID-19 pandemic and the infection control measures used will serve as a useful starting point. However, a major lesson from this pandemic has been that infection control measures need to be regularly adapted based on emerging information. State and federal decision makers, as well as local authorities implementing policies, benefit from up-to-date data and concurrent analyses, and a rapid assessment of specific risks.

This research indicates that a retrospective assessment of health authority data can provide valuable insights into past policies and their practical application. Further research of contact tracing data from RNK/HD would help clarify the transmission pathways of SAR-CoV-2 within and between age groups and other social groups.

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Conflicts of Interest

The authors have no financial conflicts of interest to disclose.

Abbreviations

COVID-19: Coronavirus disease 2019
GDPR: General Data Protection Regulations (EU)
IfSG: Infektionsschutzgesetz / Infection Act
PPV: positive predictive value
RKI: Robert Koch Institute
RNK/HD: Rhine-Neckar district and Heidelberg city
RR: risk ratio
RT-PCR: reverse transcription polymerase chain reaction
SARS-CoV-2: severe acute respiratory syndrome coronavirus 2
95%CI: 95% confidence interval

Appendix – Supplementary Tables

Table 5: Proportion of additional younger age group in total population, infected, quarantined and fatalities during first five phases of the COVID-19 pandemic.

Table 6: Data record summary.

Table 7: Risks and relative risks of quarantine, infection and death during first five phases of the pandemic of young, adult and elderly people.

Table 8: Proportion, risk and relative risk of infection, quarantine and death in women and men, and in Heidelberg and Rhein-Neckar-Kreis.

Table 9: Quarantine / contact tracing Fβ score, sensitivity, positive predictive value (PPV) and ratio of quarantine to cases within different age groups during first 5 phases of COVID-19 pandemic.

Table 10: Risks and relative risks of quarantine, infection and death during first five phases of the pandemic of very young, young (additional sub-groupings), adult and elderly people.

Table 11: Infection and quarantine contingency tables with unweighted F-score.

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Supplementary Files

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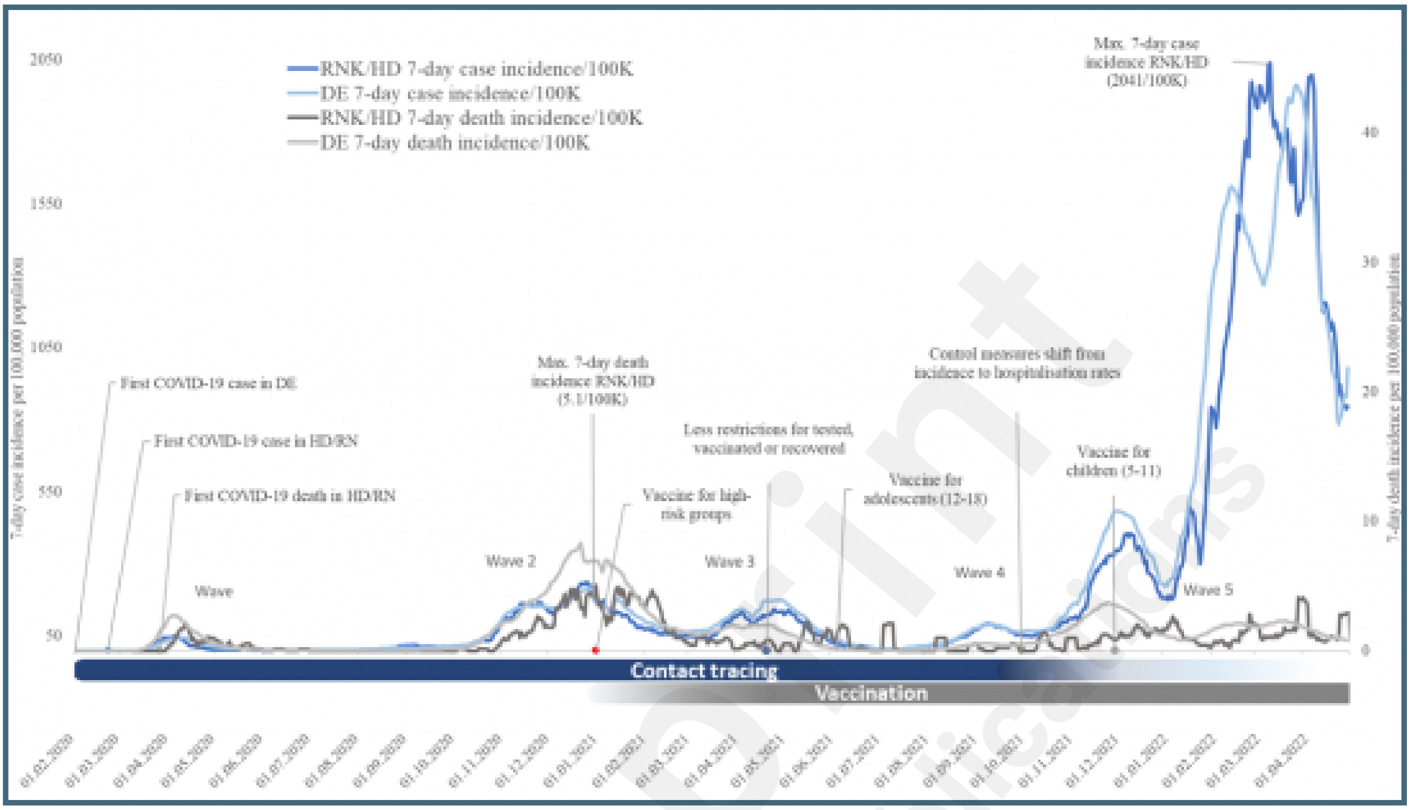
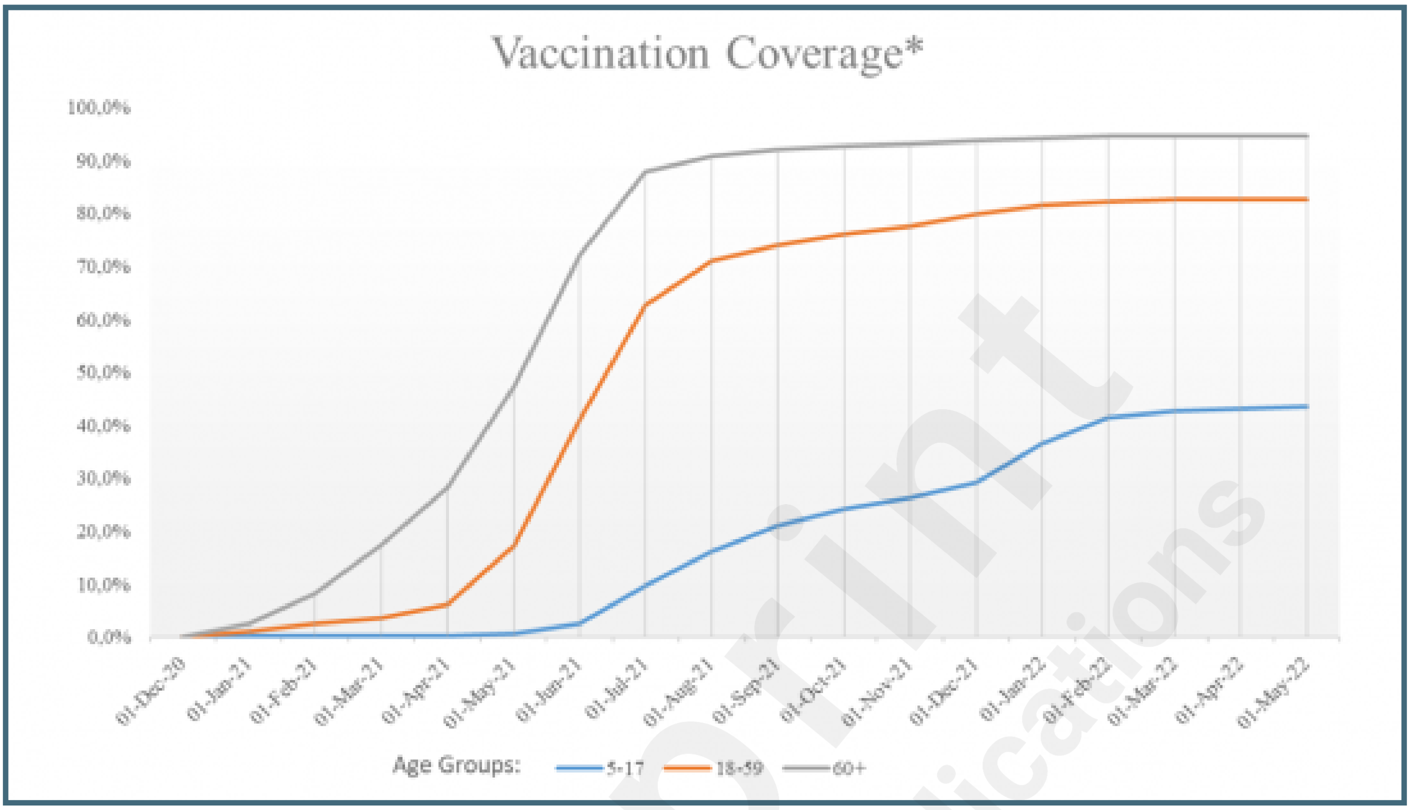
URL: http://asset.jmir.pub/assets/93452c4985e346b9d660714f0c693864.docx

Figures

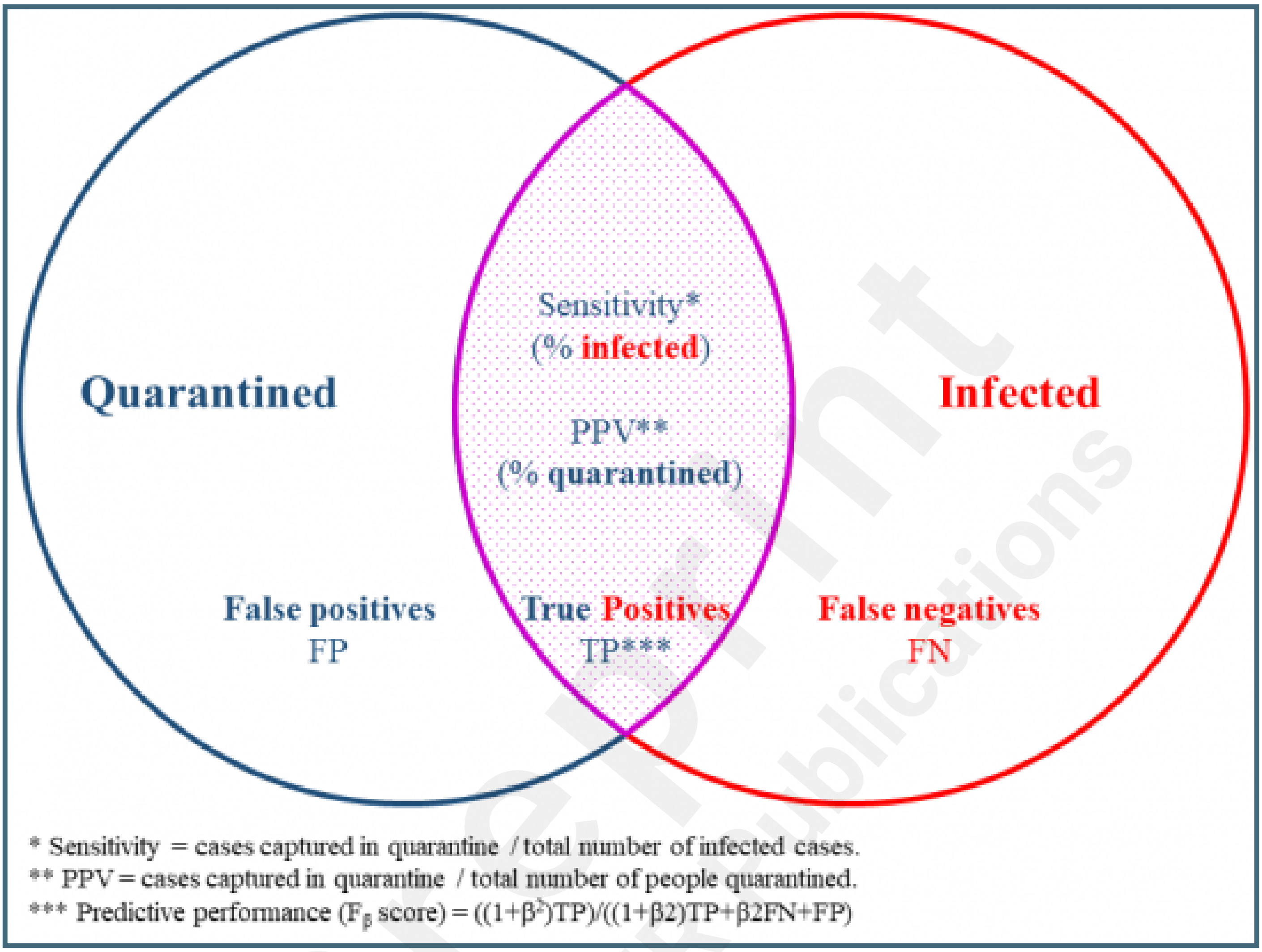
Timeline of initial COVID-19 disease incidence (morbidity) and death (mortality), with critical events including period of contact tracing and the introduction of the vaccine in RNK/HD, Germany.



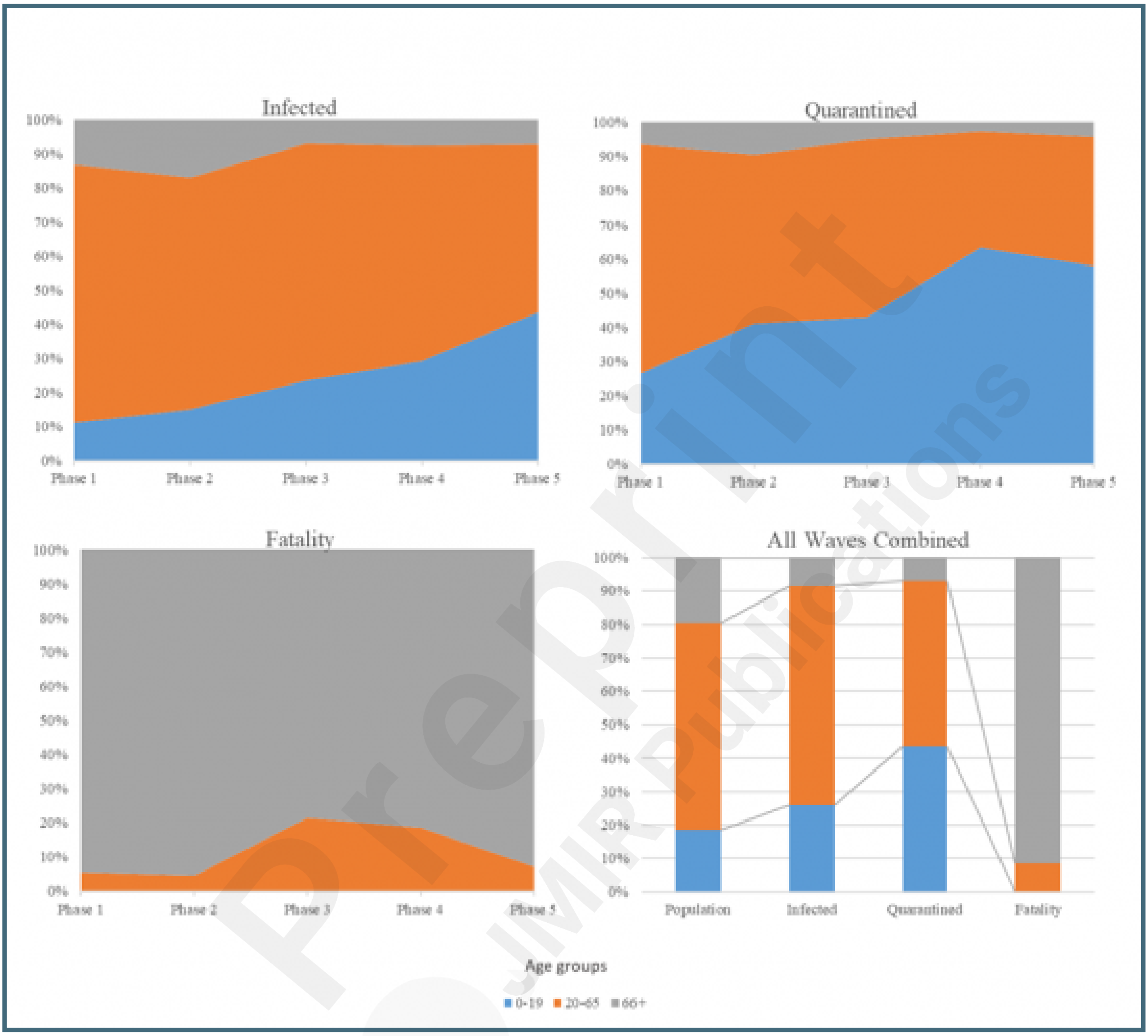
COVID-19 vaccination coverage in RNK/HD from January 2021 to May 2022 (41).



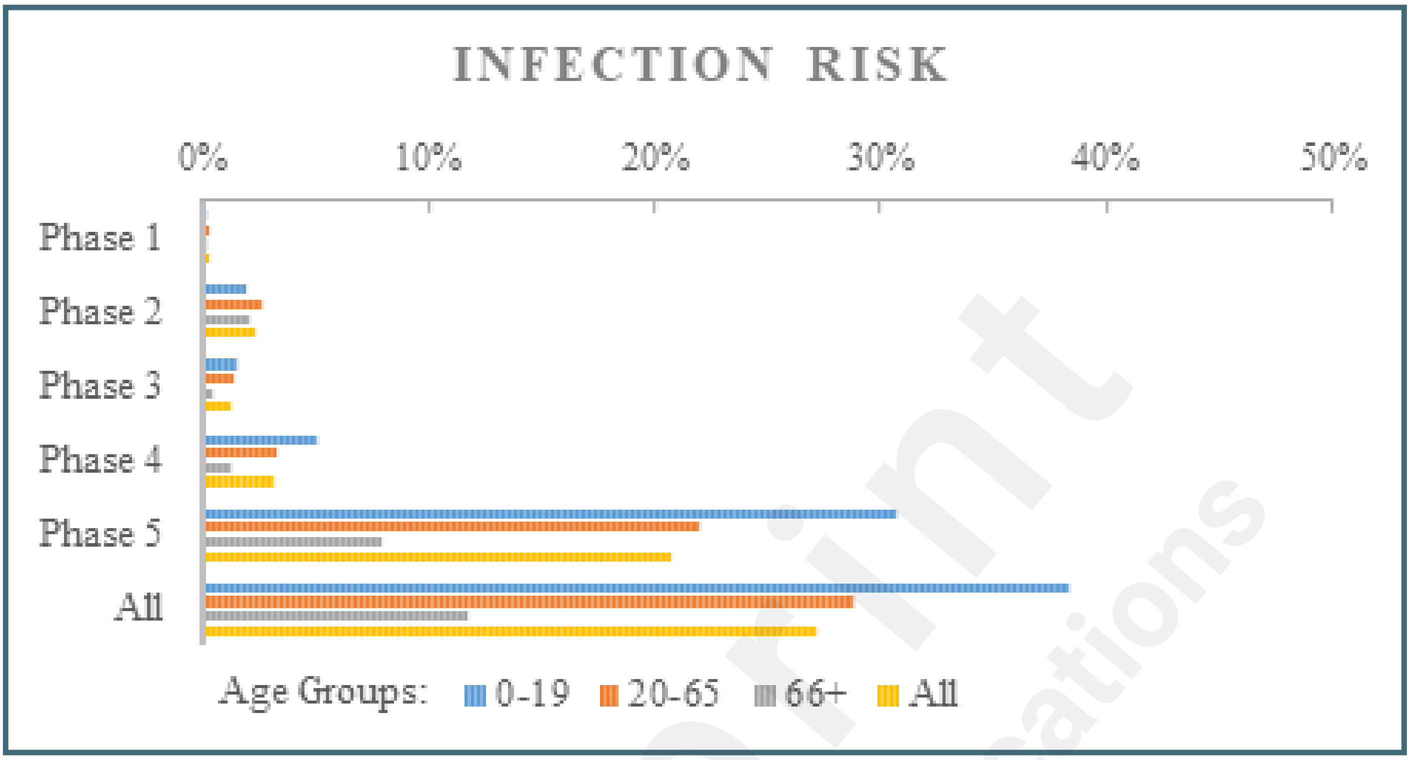
Quarantine sensitivity, positive predictive value (PPV) and F? score.



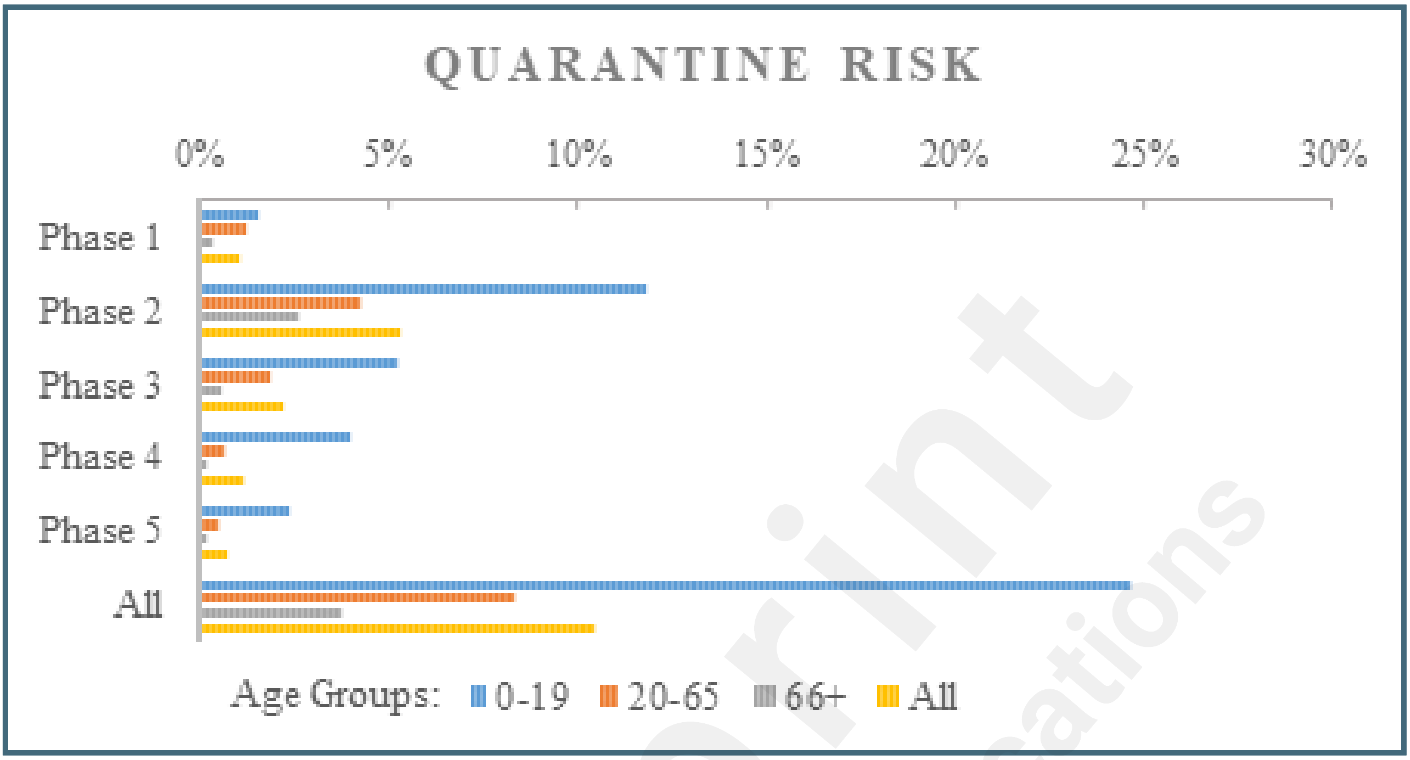
Proportion of COVID-19 related infections, quarantine and death cases, by age group and pandemic phase (stacked area/columns) from 27 January 2020 until 30 April 2022.



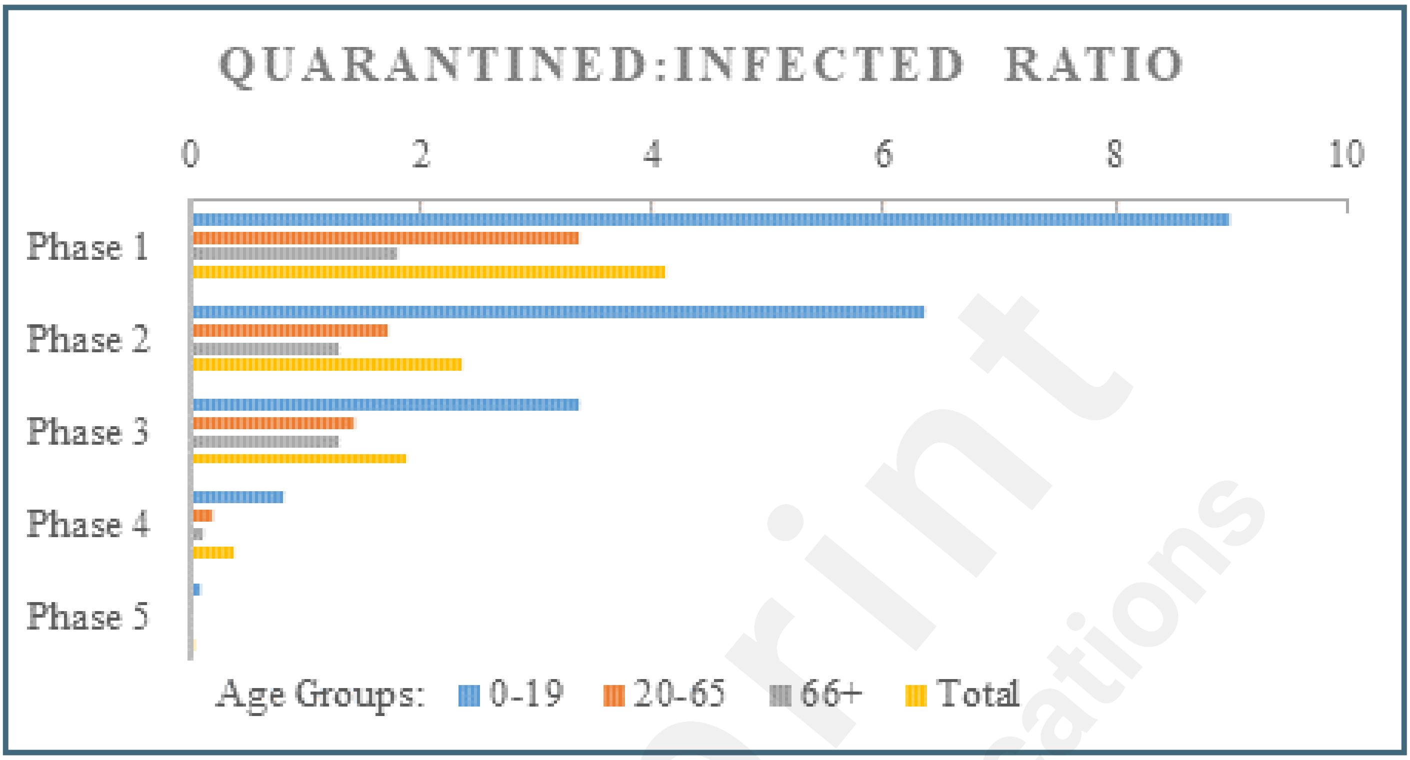
Age group risk of COVID-19 infection during the intial 5 phases of the pandemic.



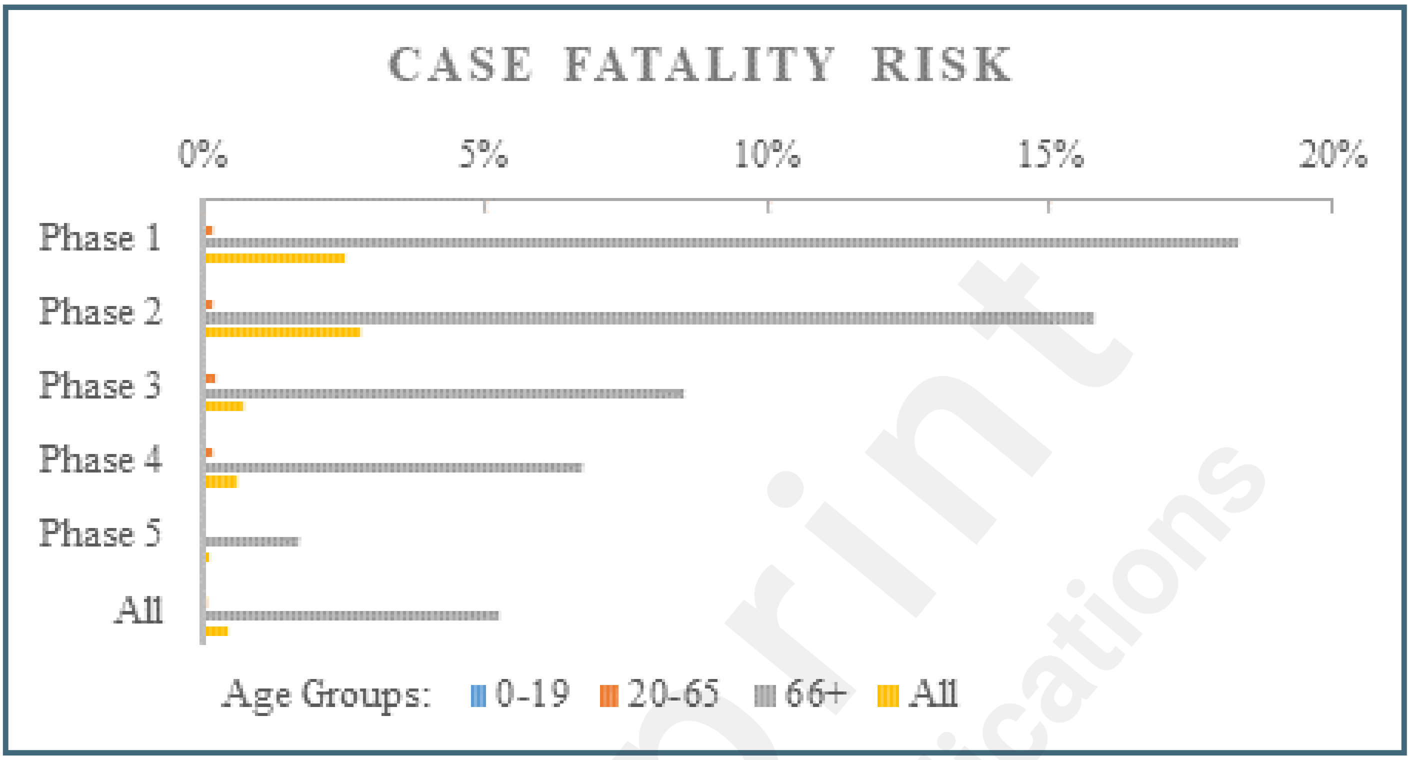
Age group risk of quarantine during the initial 5 phases of the COVID-19 pandemic.



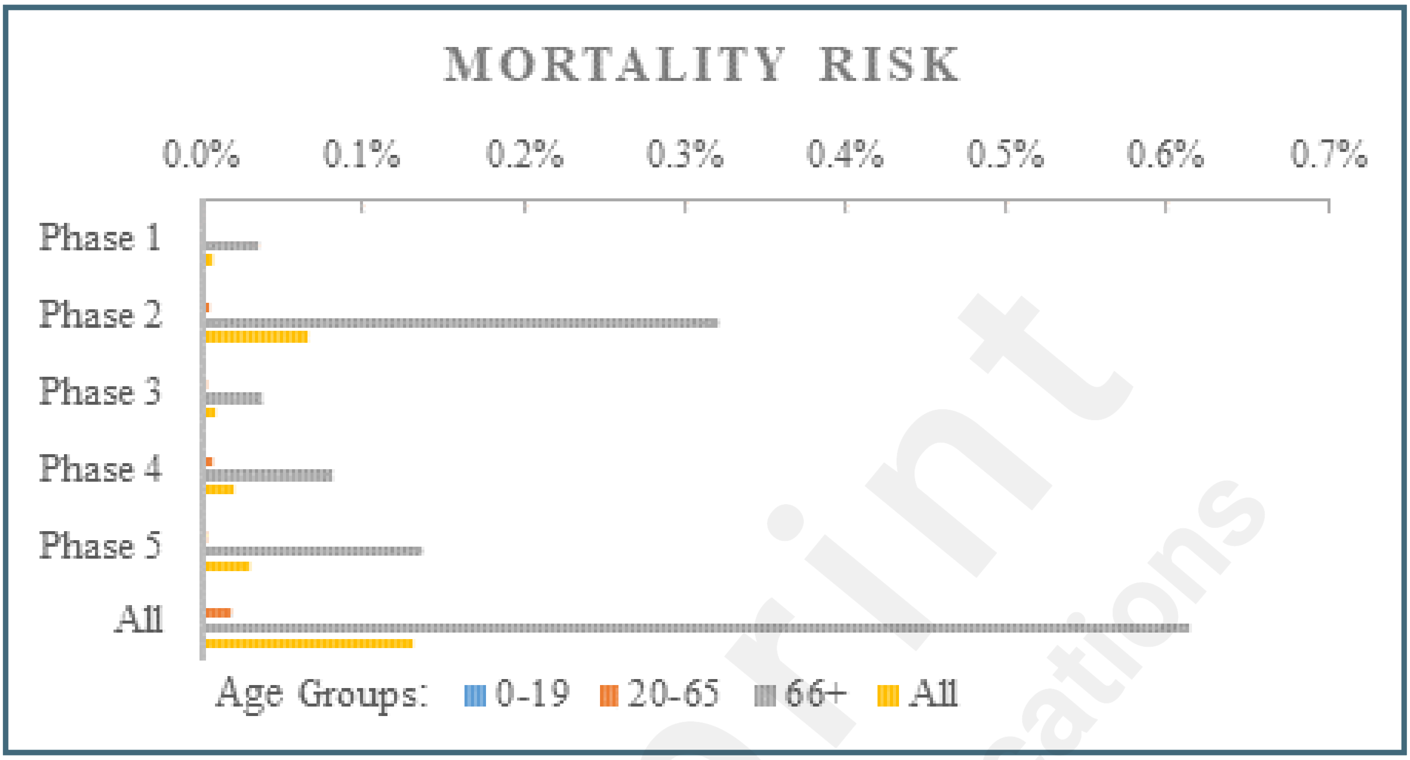
Ratio of quarantine events to COVID-19 cases during the initial 5 phases of the pandemic.



Age group risk of death following COVID-19 infection (case fatality) during the initial 5 phases of the pandemic.

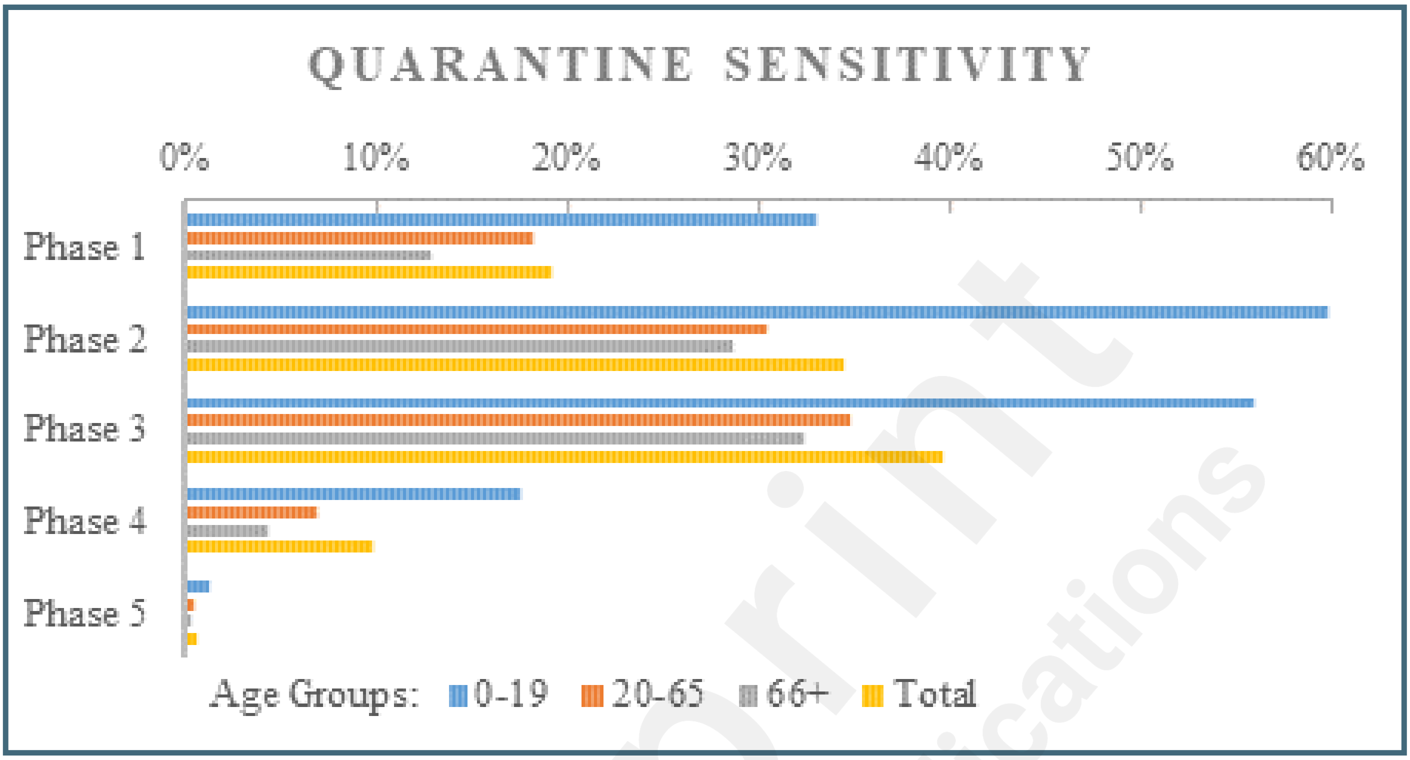


Age group risk of COVID-19 related death (mortality) during the initial 5 phases of the pandemic.

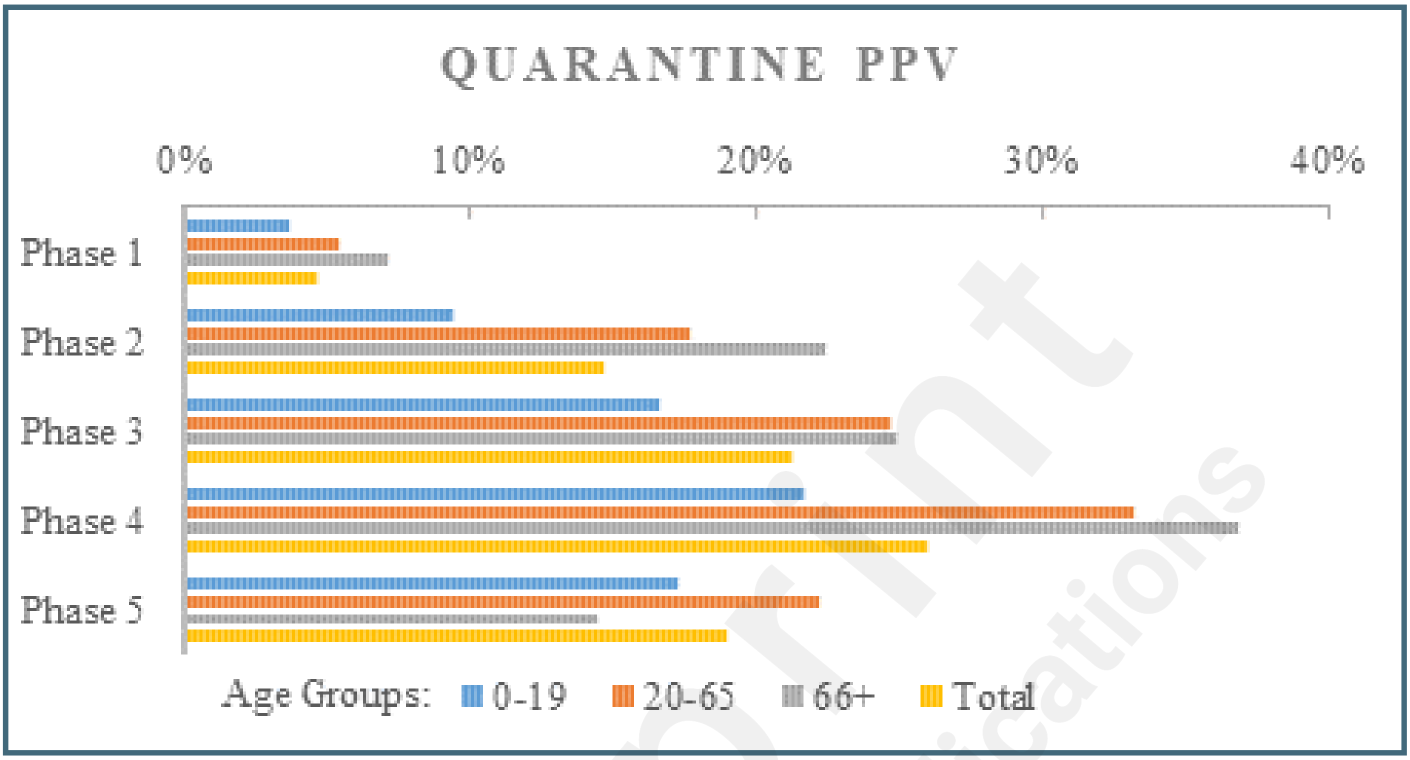


Proportional Venn diagrams of COVID-19 infections captured in quarantine (sensitivity) and within quarantined population (PPV) providing elements for predictive performance (F-score) calculations in age groups and phases of the pandemic.

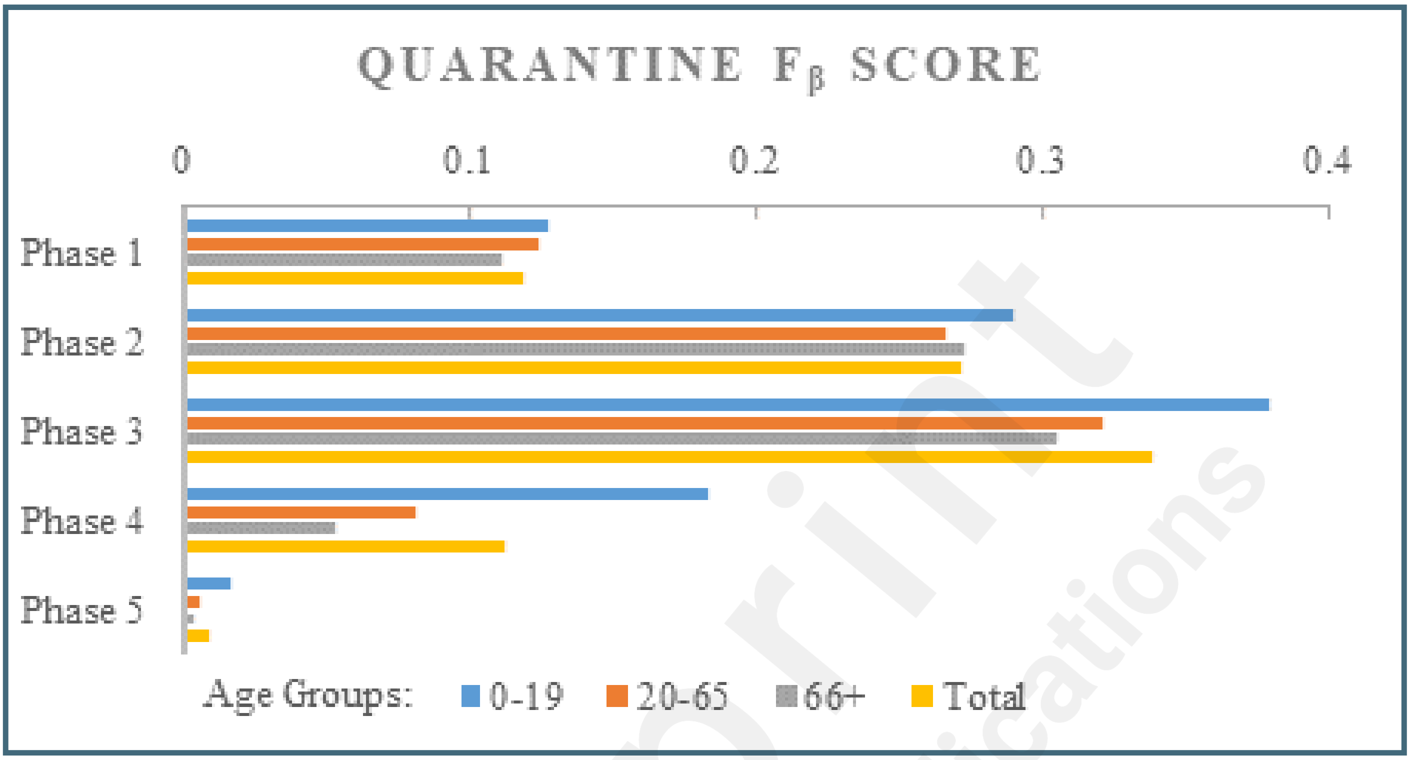
Age group quarantine sensitivity (% cases captured in quarantine) during the first 5 phases of the COVID-19 pandemic.



Age group quarantine PPV (% quarantine population infected) during the first 5 phases of the COVID-19 pandemic.



Age group quarantine predictive performance (?=2, weighted towards sensitivity) during the first 5 phases of the COVID-19 pandemic.



TOC/Feature image for homepages

Quarantine Sensitivity and PPV. Sensitivity: proportion of infections captured in quarantine. PPV: proportion of quarantine population testing positive.