Transmission dynamics, serial interval and epidemiology of COVID-19 diseases in Hong Kong under different control measures [version 1; peer review: awaiting peer review]

Yung-Wai Desmond Chan¹,², Stefan Flasche², Tin-Long Terence Lam¹, Mei-Hung Joanna Leung¹, Miu-Ling Wong¹, Ho-Yeung Lam¹, Shuk-Kwan Chuang¹

¹Communicable Disease Branch, Centre for Health Protection, Department of Health, 147C Argyle Street, Kowloon, Hong Kong
²Department of Infectious Disease Epidemiology, Faculty of Epidemiology and Population Health, London School of Hygiene and Tropical Medicine, London, UK

Abstract

Background: The outbreak of coronavirus disease 2019 (COVID-19) started in Wuhan, China in late December 2019, and subsequently became a pandemic. Hong Kong had implemented a series of control measures since January 2020, including enhanced surveillance, isolation and quarantine, border control and social distancing. Hong Kong recorded its first case on 23 January 2020, who was a visitor from Wuhan. We analysed the surveillance data of COVID-19 to understand the transmission dynamics and epidemiology in Hong Kong.

Methods: Based on cases recorded from 23 January to 6 April 2020, we constructed the epidemic curve of daily COVID-19 incidence and used this data to estimate the time-varying reproduction number ($R_t$) with the R package EpiEstim, with serial interval computed from local data. We described the demographic and epidemiological characteristics of reported cases. We computed weekly incidence by age and residential district to understand the spatial and temporal transmission of the disease.

Results: COVID-19 disease in Hong Kong was characterised with local cases and clusters detected after two waves of importations, first in late January and the second one in early March. The $R_t$ increased to approximately 2 and approximately 1, respectively, following these importations; it decreased to below 1 afterwards, which coincided with the implementation, modification and intensification of different control measures. Compared to local cases, imported cases were younger (mean age: 52 years among local cases vs 35 years among imported cases), had a lower proportion of underlying disease (9% vs 5%) and severe outcome (13% vs 5%). Cases were recorded in all districts but the incidence was highest in those in the Hong Kong Island region.

Conclusions: Stringent and sustained public health measures at population level could contain the COVID-19 disease at a relatively low level.
Keywords
COVID-19, SARS-CoV-2, transmission potential, reproduction number, serial interval

This article is included in the Coronavirus (COVID-19) collection.

Corresponding author: Yung-Wai Desmond Chan (yung-wai.chan@lshtm.ac.uk)

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Introduction
In December 2019, a cluster of pneumonia cases with unidentified etiology was reported in Wuhan, China\(^1\). The cause was later identified in early January as a novel type of coronavirus, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), for which the World Health Organization (WHO) later named the disease as coronavirus disease 2019 (COVID-19)\(^2\). It sparked an outbreak in Wuhan and spread to other parts of China. The WHO declared this outbreak a Public Health Emergency of International Concern on 30 January 2020 and further characterised it as a pandemic on 11 March 2020\(^3\). As at 14 April 2020, there were over 1,800,000 confirmed cases with over 117,000 deaths affecting many countries and areas around the world\(^4\).

Hong Kong recorded the first imported case from Wuhan, China on 23 January 2020 and over 700 cases were recorded by the end of March 2020. Local cases and clusters were identified after different waves of importation, first from Mainland China in late January and other parts of the world in March. A series of control measures had been implemented and intensified over the course of the epidemic including enhanced surveillance, isolation and quarantine, border control and social distancing (Table 1). This report summarises the transmission dynamics and the epidemiology of COVID-19 in Hong Kong from late January to early April 2020.

Methods
In Hong Kong, the Centre for Health Protection (CHP) of the Department of Health conducted surveillance for COVID-19 for early detection of cases through systems implemented at different levels, including statutory notification by frontline doctors\(^5\), enhanced health surveillance at border control points (e.g. temperature screening) and health declaration by visitors, enhanced laboratory surveillance on hospital inpatients, emergency departments, outpatient clinics, and asymptomatic inbound travellers\(^6\). All cases should be tested for SARS-CoV-2 by quantitative PCR (qPCR) at the Public Health Laboratory Service Branch (PHLSB) of the CHP. Seroconversion or four-fold or greater increase in antibody titre to SARS-CoV-2 in paired serum is another laboratory criterium of confirmation. Irrespective of clinical presentation, cases tested positive were classified ‘confirmed’ and those with inconclusive laboratory result but had epidemiological linkage to confirmed COVID-19 cases were considered as ‘probable’. Contact tracing would be carried out for every confirmed and probable case to identify any exposure persons who had contact with the case. They would be put under quarantine and medical surveillance. Based on the reports of daily situation updates from the CHP on these confirmed and probable cases\(^7\), and the Government’s press releases\(^8\), we collated a line-list of COVID-19 cases with basic demographic, epidemiological and clinical information including age, gender, residential status and district, date of symptom onset and date of reporting, importation status and discharge status. We regrouped the importation status based on the official case classification\(^9\) and travel history of the cases before onset of symptom into “imported” and “local” (i.e. non-imported) cases (Table 2). In brief, imported cases were those with travel history who had spent a significant amount of their incubation period at a place(s) where there was evidence of local transmission, according to the WHO situation reports\(^4\) and ECDC global case update\(^10\). A total of 20 of 915 cases (2.2%) remained unclassified as they had travel history but also spent time in Hong Kong when there was local transmission.

Estimation of time-varying reproduction number
We included confirmed and probable cases reported between 23 January and 6 April 2020 into an analysis estimating the effective reproduction number and its change during the study period. We included all confirmed and probable cases. We constructed an epidemic curve of these cases. The daily number of new cases are expected to increase over time if \(R\) exceeds 1 whilst an epidemic is expected to decline if \(R\) is consistently reduced to below 1. The time-varying reproduction number (\(R_t\)) was estimated based on the daily COVID-19 incidence using the R package EpiEstim version 2.2-1\(^12\). Details of the \(R_t\) estimation were described by Wallinga et al.\(^13\), Cori et al.\(^14\) and Thompson et al.\(^15\). In brief, the average incidence of cases at time \(t\) is following a Poisson distribution mean

\[
E(I_t) = R_t \sum_{s=0}^{t-s} I_s \cdot w_s
\]

where \(R_t\) is the effective reproduction number at time \(t\), \(I_s\) is the infection incidence at time \(t - s\) and \(w_s\) is the weighted infectivity function. Since the day of infection is unknown in almost all cases, we instead use the incidence of symptomatic cases based on the reported onset date. Note that as a result our estimates of \(R_t\) for infection incidence are therefore shifted by about 5 days\(^16\).

We fit the incidence data by date of onset with a time window of 7 days to compute the \(R_t\). For asymptomatic cases, their date of reporting was used instead. Case ID 503, who had been residing in Spain and returned to Hong Kong on 26 March, was tested positive upon arrival. As he had chronic cough since January but no other symptoms at the time of confirmation his date of arrival was used as date of onset. The daily incidence was stratified by the importation status of cases (imported and likely locally acquired). For unclassified cases after regrouping, we conducted separate estimates by either including them either as imported or local. For the 915 cases recorded during the study period, 67 cases picked up at borders were not included in the \(R_t\) estimation, as their risk of transmission to the community was considered minimal. We reviewed reported cases among different clusters and identified 47 pairs of symptomatic infectors and infectees with clear epidemiological evidence of a direct transmission link (Table 3). All infectees identified had direct exposure to the respective infectors and no exposure with other known confirmed cases. The corresponding serial interval was computed as the difference in days between disease onset of these successive cases, which approximated the interval between generations of infections\(^17\). A gamma distribution was fit to the serial interval data and was used as the weighted infectivity function (\(w_s\)) in the \(R_t\) estimation. Four sensitivity analyses were carried out to assess the impact of data source (using all incidence cases with and without stratification into imported and
Table 1. Key control measures implemented to combat COVID-19 in Hong Kong from Jan to Mar 2020.

<table>
<thead>
<tr>
<th>2020</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of cases in HK (imported)</td>
<td>13 (11)</td>
<td>82 (12)</td>
<td>620 (436)</td>
</tr>
</tbody>
</table>

Key events
- Outbreaks in Wuhan and other parts of China started
- Outbreaks in South Korea, Iran and part of Italy
- Increasing number of cases worldwide
- WHO declared pandemic

1. Enhanced surveillance and management of cases
   a. Case based detection
      Reporting criteria
      On 31 Dec 2019, a reporting criteria was developed and a surveillance system has been launched immediately to trace suspected cases. The reporting criteria has been revised from time to time according to the latest situation.
      Statutory reporting
      Legal Ordinance was amended to include “Severe Respiratory Disease associated with a Novel Infectious Agent” as a statutorily notifiable infectious disease since 8 Jan 2020. New regulations were made for compulsory quarantine and information disclosure to facilitate investigation and control measures.

b. Enhanced laboratory surveillance at population level
   Free COVID-19 testing at different settings
   • Since mid-Jan, certain groups of in-patients with pneumonia (e.g. ICU) were tested for COVID-19.
   • Since late Jan, testing was further extended to all inpatients with pneumonia (irrespective of travel history).
   • Since mid-Feb, symptomatic patients attending General Outpatient Clinics (GOPC) and Accident and Emergency Departments (AED) were offered tests for COVID-19.
   • Since early Mar, testings were provided to symptomatic patients attending private medical practitioners.
   • Since late Mar, testings were provided to asymptomatic inbound travellers from UK, Europe and US; later extended to cover all asymptomatic inbound travellers.

   c. Isolation and quarantine
      Confirmed or symptomatic suspected cases
      Isolation and treatment were provided in hospital until physically fit for discharge and having negative PCR results in 2 consecutive days.
      Close contacts
      14-day quarantine at quarantine centres
      Persons from places with high risk of COVID-19 transmission
      • 14-day quarantine at quarantine centres or home quarantines;
      • The list of areas/places expanded from Hubei province in late Jan to Mainland China on 8 Feb; further included South Korea, Iran and parts of Italy in late Feb; expanded to parts of France, Germany, Spain and Japan in early Mar; and later included all overseas places in mid-Mar.

2. Border control
   Reducing flow of people from Mainland China and other places
   • Since 27 Jan, Hubei residents have been restricted from entering HK
   • Since 28 Jan, transport services and border control point services to-and-from Mainland China were reduced or suspended gradually (flights, railway, ferry, cruise terminal, ocean terminal, land-based cross-boundary transport).
   • Since 8 Feb, all people entering HK from the Mainland were required to undergo 14-day mandatory quarantine.
   • Since 24 Feb, Red Outbound Travel Alert (OTA) was issued on South Korea and later expanded to parts of Italy; travellers from there would be subject to compulsory quarantine/medical surveillance.
   • Since 10 Mar, Red OTA was expanded to other countries/territories gradually.
   • Since 19 Mar, people from all overseas places in the past 14 days would be subject to compulsory quarantine.
   • Since 25 Mar, all non-HK residents coming from overseas would be denied entry. All transit services at the airport were suspended. All travellers coming from Macao and Taiwan would be subject to compulsory quarantine.

   Enhanced health surveillance measures at border control points
   • Since 1 Jan, inbound travellers with relevant symptoms and travel or exposure history identified would be referred to public hospitals for isolation.
   • Additional temperature screening of inbound travellers from Wuhan; later expanded to inbound travellers from Mainland China.
   • Since 1 Feb, travellers departing and on transit from the airport were required to undergo temperature checks; exit screening was later expanded to Cruise and Ocean Terminal.
   • Since late Feb, additional temperature checks had been conducted for travellers from Korea.
   • Enhanced temperature screening to all inbound travellers.
2020 | Jan | Feb | Mar
--- | --- | --- | ---
No. of cases in HK (imported) | 13 (11) | 82 (12) | 620 (436)

Key events
- Outbreaks in Wuhan and other parts of China started
- Outbreaks in South Korea, Iran and part of Italy
- Increasing number of cases worldwide
- WHO declared pandemic

Health declaration
- Since 21 Jan, inbound passengers from Wuhan by air are required to complete a health declaration form, later expanded to high speed rail and then all passengers from Mainland China.
- Since 1 Feb, health declaration arrangements were expanded to other border control points (land, sea) gradually.
- Since 25 Feb, health declaration form is required for all inbound flights from Korea.
- Since 8 Mar, the health declaration arrangements have been expanded to all flights arriving HK.

3. Non-pharmaceutical public health measures

a. Infection Control

Public
- Since 1 Jan, health promotion and education activities to enhance personal, respiratory, environmental hygiene and travel health advice through website, social media, TV and radio APIs, advertisements, press releases, health talks, etc.
- Health education materials (e.g. infographics, pamphlets, posters) are translated and made available to nine ethnic minorities, which have been disseminated to different stakeholders and sectors.
- Telephone hotline was set up to provide information and answers to questions.

Community
- Cleaning was stepped up in premises where cases have stayed. Cleaning of public area and facilities, such as lifts and escalators, was enhanced.
- Infection control measures were implemented at government buildings and offices, such as temperature checking and providing alcohol hand sanitisers, etc.
- Infection control guidelines were developed for community settings (e.g. schools, workplace, institutions, hotel industry, public transport, property management, etc.)
- Letters/emails to schools, institutions, private hospitals and clinics, trade and industry, non-government organisations and other community partners on infection control measures.

Healthcare
- Infection control measures were strengthened in hospitals, clinics and health service centres.
- Infection control trainings were provided to healthcare professionals in public and private sectors.
- Infection control guidelines were developed for different healthcare settings and healthcare professionals.
- Since 26 Jan, visiting, volunteer activities and clinical placement were suspended in public hospitals; all persons in public hospital areas required to wear mask.

b. Social distancing

Work
- From late Jan to early Mar, civil servants were allowed to work from home (except emergency and essential public services). The Government also appealed to other employers to make flexible work arrangements for employees to reduce social contacts.
- From early Mar to late Mar, public services were gradually resumed, but flexible working hours and roster adopted.
- Since late Mar, special work arrangement was made for civil servants. All government departments would provide essential, emergency and limited public services only.

Education
- Since late Jan, schools including tutorial centres were suspended until further notice. Online teaching was adopted.
- The Hong Kong Diploma of Secondary Education (HKDSE) examinations were postponed from Mar to late Apr.

Community
- Since late Jan, mass gathering events and recreational facilities have been cancelled or closed, e.g. the Hong Kong marathon, large-scale concerts, public libraries, Disneyland and Ocean Park, etc.
- Since late Mar, more outdoor leisure facilities were closed, e.g. sports facilities, playgrounds, etc.
- In late Mar, new regulations were made to impose temporary restriction on seating capacity and distance between tables at catering premises, temporary closure of scheduled premises (e.g. cinema), and prohibit any group gathering of more than 4 persons in any public place.
Table 2. Classification of importation status for cases included in the analyses (n = 915).

<table>
<thead>
<tr>
<th>Official case classification</th>
<th>Regrouped importation status</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imported</td>
<td>Imported</td>
<td>526</td>
</tr>
<tr>
<td>Local case</td>
<td></td>
<td>63</td>
</tr>
<tr>
<td>Close contact of imported case</td>
<td>Local</td>
<td>21</td>
</tr>
<tr>
<td>Close contact of local case</td>
<td></td>
<td>155</td>
</tr>
<tr>
<td>Close contact of possibly local case</td>
<td></td>
<td>48</td>
</tr>
<tr>
<td>Close contact of local case</td>
<td>Unclassified</td>
<td>3</td>
</tr>
<tr>
<td>Possibly local</td>
<td>Imported</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>Local</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Unclassified</td>
<td>17</td>
</tr>
</tbody>
</table>

1Cases had contracted infections in Hong Kong with various source of infection and had no travel history 14 days before onset of symptoms/confirmation of infection. All were regrouped as local cases.
2Cases remained unclassified as they had travel history but also spent time in Hong Kong when there was local transmission.
3Cases had travel history during their incubation period to places with high risk of COVID-19 transmission.
4One case did not have any travel history during his incubation period and the other case with travel history was linked to a local cluster.

Table 3. Infector-infectee pairs used to compute local serial interval data.

<table>
<thead>
<tr>
<th>Setting</th>
<th>Case No From</th>
<th>Onset date From</th>
<th>Serial interval (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household</td>
<td>85 90</td>
<td>12-02-20</td>
<td>4</td>
</tr>
<tr>
<td>Household</td>
<td>92 95</td>
<td>13-02-20</td>
<td>16</td>
</tr>
<tr>
<td>Household</td>
<td>106 116</td>
<td>04-03-20</td>
<td>3</td>
</tr>
<tr>
<td>Household</td>
<td>143 155</td>
<td>11-03-20</td>
<td>4</td>
</tr>
<tr>
<td>Household</td>
<td>143 298</td>
<td>11-03-20</td>
<td>9</td>
</tr>
<tr>
<td>Household</td>
<td>154 228</td>
<td>11-03-20</td>
<td>7</td>
</tr>
<tr>
<td>Household</td>
<td>154 311</td>
<td>11-03-20</td>
<td>8</td>
</tr>
<tr>
<td>Social</td>
<td>169 208</td>
<td>16-03-20</td>
<td>2</td>
</tr>
<tr>
<td>Social</td>
<td>174 162</td>
<td>09-03-20</td>
<td>3</td>
</tr>
<tr>
<td>Household</td>
<td>174 222</td>
<td>09-03-20</td>
<td>9</td>
</tr>
<tr>
<td>Workplace</td>
<td>174 243</td>
<td>09-03-20</td>
<td>4</td>
</tr>
<tr>
<td>Workplace</td>
<td>174 285</td>
<td>09-03-20</td>
<td>11</td>
</tr>
<tr>
<td>Workplace</td>
<td>174 243</td>
<td>09-03-20</td>
<td>4</td>
</tr>
<tr>
<td>Workplace</td>
<td>174 285</td>
<td>09-03-20</td>
<td>11</td>
</tr>
<tr>
<td>Household</td>
<td>195 322</td>
<td>17-03-20</td>
<td>4</td>
</tr>
<tr>
<td>Dating</td>
<td>243 349</td>
<td>13-03-20</td>
<td>6</td>
</tr>
<tr>
<td>Social</td>
<td>338 229</td>
<td>11-03-20</td>
<td>7</td>
</tr>
<tr>
<td>Social</td>
<td>338 337</td>
<td>11-03-20</td>
<td>8</td>
</tr>
<tr>
<td>Household</td>
<td>347 709</td>
<td>22-03-20</td>
<td>7</td>
</tr>
<tr>
<td>Household</td>
<td>447 912</td>
<td>24-03-20</td>
<td>3</td>
</tr>
<tr>
<td>Household</td>
<td>447 913</td>
<td>24-03-20</td>
<td>3</td>
</tr>
<tr>
<td>Household</td>
<td>462 515</td>
<td>23-03-20</td>
<td>2</td>
</tr>
<tr>
<td>Social</td>
<td>462 757</td>
<td>23-03-20</td>
<td>7</td>
</tr>
<tr>
<td>Household</td>
<td>477 525</td>
<td>22-03-20</td>
<td>2</td>
</tr>
<tr>
<td>Social</td>
<td>483 516</td>
<td>18-03-20</td>
<td>7</td>
</tr>
<tr>
<td>Beauty salon</td>
<td>504 756</td>
<td>25-03-20</td>
<td>4</td>
</tr>
<tr>
<td>Household</td>
<td>513 810</td>
<td>24-03-20</td>
<td>9</td>
</tr>
<tr>
<td>Neighbour</td>
<td>525 760</td>
<td>24-03-20</td>
<td>7</td>
</tr>
<tr>
<td>Household</td>
<td>581 691</td>
<td>24-03-20</td>
<td>5</td>
</tr>
<tr>
<td>Household</td>
<td>746 844</td>
<td>26-03-20</td>
<td>7</td>
</tr>
<tr>
<td>Social</td>
<td>756 796</td>
<td>29-03-20</td>
<td>1</td>
</tr>
</tbody>
</table>

local, using local and unclassified cases only as well as using local cases only), source of serial interval (using local serial interval data and serial intervals reported in two other studies\textsuperscript{(18,19)}, exclusion of cases identified by contact tracing and size of time window (4, 7 and 14 days).
Descriptive epidemiology
We described the demographic and epidemiological characteristics of these cases. We compared the age- and sex-specific proportion of cases with the Hong Kong demographics in 2019\(^{35}\). To understand the spatial and temporal distribution of the disease in the community, we computed incidence by age and residential district in different weeks of disease onset. We excluded cases picked up at borders as well as those with unknown residential district from the spatial analysis. We described the temporal trend of the onset, report, death or discharge of cases and utility of hospital beds with data provided by the Hong Kong SAR Government\(^9\). We computed the duration between onset to report with time, as well as the duration between report to discharge over time and age.

Results
Estimation of \(R_t\)
From 23 January to 6 April 2020, 915 COVID-19 cases were recorded with 606 (66%) being imported (Table 4). The epidemic started with imported cases from the Mainland China (Figure 1), followed by cases with no travel history and no known contacts with imported cases. The first case was a febrile 39-year-old visitor from Wuhan intercepted at the border by the Port Health Division (PHD) of the DH and was later confirmed for COVID-19 on 23 January (Week 3). One week later the first non-imported case with symptom onset on 22 January was reported, followed by emergence of first wave of cases around the period of Chinese New Year holiday (week 4 to 6). These included two large clusters involving family

<table>
<thead>
<tr>
<th>Table 4. Characteristics of COVID-19 cases in Hong Kong reported from 23 January to 6 April 2020 (n = 915).</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Local</strong></td>
</tr>
<tr>
<td>--------</td>
</tr>
<tr>
<td>n (%)</td>
</tr>
<tr>
<td>Male gender</td>
</tr>
<tr>
<td>Age (mean (SD))</td>
</tr>
<tr>
<td>Age group</td>
</tr>
<tr>
<td>0 to 9</td>
</tr>
<tr>
<td>10 to 19</td>
</tr>
<tr>
<td>20 to 29</td>
</tr>
<tr>
<td>30 to 39</td>
</tr>
<tr>
<td>40 to 49</td>
</tr>
<tr>
<td>50 to 59</td>
</tr>
<tr>
<td>60 to 69</td>
</tr>
<tr>
<td>70 to 79</td>
</tr>
<tr>
<td>80+</td>
</tr>
<tr>
<td>Hong Kong residents</td>
</tr>
<tr>
<td>HK resident</td>
</tr>
<tr>
<td>Non-HK resident</td>
</tr>
<tr>
<td>Asymptomatic when reported</td>
</tr>
<tr>
<td>Any underlying disease</td>
</tr>
<tr>
<td>Hospitalisation status</td>
</tr>
<tr>
<td>Deceased</td>
</tr>
<tr>
<td>Discharged</td>
</tr>
<tr>
<td>Still hospitalised</td>
</tr>
<tr>
<td>Pending admission</td>
</tr>
<tr>
<td>Ever serious/under ICU care for discharged or deceased cases(^1)</td>
</tr>
<tr>
<td>Duration between onset and report (median [IQR])</td>
</tr>
</tbody>
</table>

\(^1\)According to information reported by the Hospital Authority (HA) during the daily press conference. Serious cases were those who required high-flow oxygen.
Figure 1. Epidemic curve and time-varying reproduction number estimates for COVID-19 cases in Hong Kong by date of onset (n = 848). Note: 915 cases reported from 23 Jan to 6 Apr 2020. 67 cases picked up at borders were not included in the $R_t$ estimation and was not shown in the epicurve in the first plot; $R_t$ estimates of last 7 days was not shown as it was likely under-estimated due to the delay between disease onset and report.

gatherings, each led to onward transmission in households or workplace with 13 and 6 cases being eventually identified\textsuperscript{21}. In February (week 6 to 9), a majority of cases had no travel history (51 of 67, or 76%), with a large cluster of 19 persons associated with Buddhist temple in Eastern district (12 persons worked/visited this temple who then led to 7 additional secondary cases)\textsuperscript{21}. 

\textsuperscript{21}
For this wave, the $R_t$ increased from around 1.5 in week 3 to around 2 in week 4, it then gradually decreased to under 1 along with decrease in reported number of cases between week 6 to 8. The second wave started in early March (week 9 to 10), with the $R_t$ increased to around 1 with an increasing number of reported cases. Among the 436 imported cases in Mar, most had travel history to UK and other parts of Europe (321 or 74%), followed by the US (38 or 9%) and Canada (20 or 5%). More local cases and clusters associated with social activities and gatherings were reported following influx of such imported cases. For example a large cluster with over 90 persons involving a group of band players, staff and customers of restaurants and pubs, as well as onward transmission to their friends and families were identified in late March\textsuperscript{22,23}. Two other clusters involved social gatherings in Karaoke were also identified\textsuperscript{24,25}. The $R_t$ decreased to around 0.5 from weeks 11 to 13. The mean serial interval among 47 infector-infectee pairs identified was 6.5 days [standard deviation (SD) 4.7 days] (Figure 2).

Age, spatial and temporal distribution

Compared to local cases, imported cases were younger (mean age 35 years for imported cases vs 43 years for local cases) and had a higher proportion of being asymptomatic at the time of reporting (19% for imported cases vs 11% for local cases) (Table 4). Up to 6 April, 216 cases were discharged while 4 cases passed away. Among those already discharged/deceased, 8% were under intensive care unit (ICU) care or considered serious. The four fatal cases involved three males and one female aged 39 to 80 years, all were reported to have underlying illnesses.

Compared to the whole population, there was a considerably higher proportion of cases among those aged 10 to 39 years for both genders (Figure 3). In contrast, those aged under 10 and those aged 80+ only contributed to 1% each among the reported cases, which was substantially lower than their respective distribution in the population. The age-specific incidence varied greatly by weeks of disease onset (Figure 4b). The incidence for those aged 60 to 79 was higher among those in weeks 4 to 7 and remained stable until a surge in weeks 11 and 13 which coincided with a rapid increase in incidence for those aged 10 to 39, for which the incidence had been low. The incidence for those aged under 10 was all along lowest as no cases were recorded until week 11 and 12.

Geographically, the incidence per 100,000 was highest in the districts in the Hong Kong Island region of the city (Wan Chai: 480 and Central and Western: 357) and was considerably lower in the New Territories region (under 40 for Yuen Long and Tsuen Wan) and lowest in the Wong Tai Sin district\textsuperscript{11} of the Kowloon Peninsula region (Figure 4a). Despite of the overall geographical difference, the increase in incidence after week 10 was observed in most districts (Figure 4c). The incidence for the extremes of age was still low even in Hong Kong Island region, despite the overall high incidence in this area (Figure 4d).

Trend of case onset, confirmation and discharge/death

All cases reported from week 4 to 7 were symptomatic. The proportion of asymptomatic cases increased to 20% in week 13. The rates of disease onset and report remained stable until the upsurge after week 10. The stable rate of discharge could not catch up with the rapid increase in the report of confirmed cases in weeks 11 and 12 (Figure 5a). Correspondingly, the daily bed usage for investigation of suspected cases and management for

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Figure 2. Gamma distribution fitted to serial interval data of COVID-19 cases in Hong Kong.
Figure 3. Proportion of COVID-19 cases in Hong Kong by age and sex in comparison to the population, reported from 23 January to 6 April 2020 (n = 915). The proportion of cases by age and sex was compared to those in the whole population. Those aged 10 to 39 years attributed to a higher proportion for both sexes among the cases reported.

Figure 4. Incidence of COVID-19 cases reported from 23 January to 6 April 2020 by age, week of onset and residential district (n = 837). In total, 837 of 915 cases (91%) were included in the above analyses. Cases detected at border or those with no known information on residential district were excluded. Hong Kong is divided into 18 districts and these districts are grossly grouped into different regions: New Territories West (Yuen Long, Tuen Mun, Kwai Tsing, Tsuen Wan), New Territories East (North, Tai Po, Sha Tin, Sai Kung), Kowloon West (Sham Shui Po, Yau Tsim Mong), Kowloon East (Kowloon City, Wong Tai Sin, Kwun Tong), Hong Kong Island (Eastern, Wan Chai, Central and Western, Southern) and Islands.
confirmed COVID-19 cases increased from under 50 to nearly 200 by week 4 and became stable at around 200 beds until week 10. The daily hospital bed usage doubled to over 400 per day in week 11, and further increased to around 600 in week 12 and 800 in week 13.

Both the median duration from onset to reporting and from reporting to discharge decreased with time as the epidemic evolved (Figure 6a, b). The duration from report to discharge decreased from 34 days in week 4 to less than 15 days from week 8 onwards (Figure 6b). This duration varied by age with a median of 8 days for those aged 20 to 29 years as compared to over 15 days for those aged 50 years and above (Figure 6c).

**Discussion**

We analysed the transmission dynamic and epidemiological characteristics of COVID-19 cases in Hong Kong in the first three months of the epidemic. The median estimated $R_t$ varied from 0.3 to 2.0 in this period and it showed that there were two waves of transmission in Hong Kong for which the $R_t$ was close to or exceeded 1, the first one following cases imported from Mainland China and the second one after imported cases from overseas places like Europe and the US. The first wave of importations occurred right before the Chinese New Year holidays and coincided with the outbreak in Wuhan and other parts of Mainland China. Transmission in the first wave was most intense at week 5 around the Chinese New Year holiday when there were increased social contacts (e.g. family gatherings). The Government implemented different measures to control the epidemic starting from January, including work from home for civil servants, school suspension, closure of recreational facilities, reducing importation pressure by closure of some border control points, enhanced laboratory surveillance for early detection of cases, etc. The transmission reduced subsequently as $R_t$ was largely below 1 in February. However, the Government departments and other companies gradually scaled back to normal services in March and social distancing might have relaxed in the community. When compared to the baseline, Google mobility data in Hong Kong showed reductions in visits to retail and recreation, parks, transit stations and workplaces in February and March. However, these indicators appeared to be lower in mid February and late March but higher in early March. These could reflect a relaxed social distancing in the community and coincided with the increase in $R_t$ in early March. Coupled with the rapid increase in number of confirmed imported cases from early March onwards, the occurrence of large clusters originated from social venues including bars and restaurants affecting over 90 persons hinted a grave risk of
Figure 6. Change in (a) duration between onset to report by onset week, (b) duration between report and discharge/death by report week and (c) by age groups. Asymptomatic cases were not included in (a). Report week 14 and those aged 0 to 9 were not shown in (b) in (c) respectively due to small numbers.
community transmission originated from importations. While the source of infection for many of these clusters was yet to be determined (e.g. before availability of genetic sequence data), the incidence was the highest among those aged 10 to 39 years for both genders, coinciding with the high number of imported cases related to returning travellers, workers and students for these highly sociable age groups in the same period. Although young adults were less likely to develop severe complications of COVID-19, they posed a risk of onward transmission to the community, including older individuals who are at higher risk of severe COVID-19 diseases. A local case of infected nurse working in a residential care home for the elderly as part of large social venue cluster further highlighted such potential risk. The second wave of epidemic led to a rapid increase in hospital bed usage for both confirmed and suspected cases. Despite a shortened duration from report to discharge and increased proportion of mild (or asymptomatic) cases, demand for isolation facility continued to stretch beyond limit along with the rapid case upsurge as two consecutive negative PCR results is one of the discharge-from-isolation of confirmed COVID-19 cases. Keeping a low level of community transmission is thus crucial in protecting the healthcare system from being overwhelmed. 

The $R_t$ estimates in Hong Kong were considerably lower than that estimated in Wuhan, which ranged from 2 to 4 when there was widespread transmission[16–18]. The lower transmissibility might be attributed by different control measures in place since January. The $R_t$ in Wuhan also decreased substantially after implementation of a series of public health interventions[19]. Of note, the majority of the Hong Kong community have been wearing masks in public areas since late January, although the effectiveness of this and other measures in reducing viral transmission at population level was still unclear[20]. Phylogenetic analyses of 50 of the first 93 cases from late January to February by Leung et al. showed that COVID-19 cases and clusters in Hong Kong was mostly propagated from two ancestors, indicating limited importation and propagation of the virus in the community during this period[21]. Spatial clustering of cases around affluent and commercial areas in the Hong Kong Island region since March might be evidence that transmission might initiate from persons with more frequent overseas travel and an increased risk of importation. Secondary transmission was still relatively confined and not yet widespread in the entire territory. 

Our $R_t$ estimates in Hong Kong were comparable to those from Abbott et al.[16] but lower than that from Cowling et al. in March[17]. Both studies also employed the R package EpiEstim. The multi-countries estimates from Abbott et al. used publicly available data with only reporting dates available and the onset dates was estimated from a reporting delay distribution[16]. Our $R_t$ estimates was largely comparable to that from Cowling et al.[17] with the exception from mid March onwards for which their $R_t$ maintained at around 1 while ours was around 0.5. As they assumed completeness of reporting imported and local cases to be 99% and 80% and adjusted both data before model fitting, the proportion of local cases increased. This should lead to higher $R_t$ estimates as local cases would account for a more significant proportion of new incident cases, as shown in our sensitivity analysis of including only local cases (Figure 7). In addition, the longer serial interval they adopted from Li et al.[24] would also result in higher $R_t$ estimate (Figure 8). Our trend of effective reproduction number dropping from around 2 in January to less than 1 in late February was consistent with the estimate from a meta-population SEIR model by Yuan et al.[25]. As a sensitivity analysis we examined the impact of excluding cases detected by contact tracing (Figure 9). We found that this would lead to more fluctuation for the estimate in March as bigger clusters were 

**Figure 7. Sensitivity analysis on source of incidence data.** We tested the effect of including different types of incidence data in this sensitivity analysis. Including only local (and unclassified) cases resulted in higher $R_t$ estimate (purple and blue lines), as the risk of local transmission resulting from imported cases was ignored. Similarly, if all cases were included but not stratified by importation status, they would result in higher $R_t$ estimates.
Figure 8. Sensitivity analysis on using different serial interval data. \( R_t \) estimates increased with serial interval.

Figure 9. Sensitivity analysis on exclusion of cases detected by different systems. We tested the effect of excluding cases detected by different systems. Excluding cases detected by contact tracing would lead to more fluctuation of the \( R_t \) estimates in March as more cases from different clusters were detected through contact tracing during this period.

detected. As containment effort had been maintained since the start of the epidemic, we expected limited change in surveillance sensitivity due to improvement in contact tracing and opted for only excluding cases detected at border in our main analysis. Our sensitivity analyses also showed that a smaller time window led to more abrupt changes in \( R \) estimates but was also subject to more statistical noise and a wider confidence bound (Figure 10). To balance the sensitivity and confidence of \( R \) estimates, we adopted a 7-day time window.

The mean serial interval estimated from our local data was shorter than the estimate by Li et al. in Wuhan (mean 7.5 days (SD 3.4)) but longer than the estimate by Nishiura et al. (mean 4.8 days (SD 2.3)) which collated data from a readily available database. Considering the serial interval of COVID-19 is shorter than those of SARS (mean 8.4 days (SD 3.8)) and MERS (mean 12.4 days (SD 2.8) in South Korea and mean 6.8 days (SD 4.1) in Saudi Arabia), early identification of cases is required to interrupt transmission. Among countries that
implemented large scale testing, South Korea had successfully contained a large outbreak in February and the current daily number of new infections remains stably at less than 100 since early March; Iceland and Germany recorded much smaller number of cases as compared to other European countries such as Italy and Spain. Wider availability of laboratory testing will shorten the delay from onset to confirmation, thus reducing the risk of onward transmission from an infectious person. Of note, similar to our observations, South Korea also detected a high incidence of young adult cases with less severe clinical manifestation. The role of early detection among these age groups and its implication in the overall prevention and control of COVID-19 disease remains an unanswered research question.

There were several limitations to our study. First, the $R_t$ estimates are subject to changes in surveillance sensitivity. With increasing testing capacity and enhanced surveillance gradually being implemented, it was likely that the surveillance system had became more sensitive and the $R_t$ in earlier period might be underestimated. Second, the $R_t$ estimate in the most recent days was likely underestimated as cases which were infected recently would not be captured by the surveillance system. Third, we used date of reporting for asymptomatic cases in computing the incidence for $R_t$ estimation, but this would likely be later than the true date of infection for which date of disease onset would be a better approximation. Fourth, we only used residential district to study the spatial distribution of the diseases but one could have been infected or infected others in places not close to their residential districts. Incorporating local movement data to study spatial distribution would require careful consideration of the time spent and the risk of being infected/passed along the infection. Regardless, residential district should be a good proxy of the geographical spread of the transmission.

In conclusion, we studied the transmission dynamics of COVID-19 in Hong Kong under two waves of importation pressure. The $R_t$ served as an indicator to the transmission potential of COVID-19 in the community and allowed us to understand the impact of control measures during an epidemic. We showed that timely implementation of control measures such as social distancing was associated with the reduction of transmissibility of the infections. Further extension of the current analyses may include short-term forecasting once the number of imported cases stabilized. The same principle for $R_t$ estimation has been extended to include contact and genetic sequence data to infer transmission network in outbreaks, which would be useful to enhance our understanding of the role of persons with different characteristics in the transmission chain.

Data availability
Source data
Data on COVID-19 cases in Hong Kong are available in the website of Government of Hong Kong SAR as csv files. Data used in the manuscript was downloaded on 14 Apr 2020.

Number of suspected cases under investigation, number of confirmed cases still under isolation and number of cases discharged: https://data.gov.hk/en-data/dataset/hk-dh-chpsebcdr-novel-infectious-agent/resource/3fa87b30a-13ea-4e44-ab44-caf72bad1ac2.


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