

Acknowledgments

We thank Jesse Gallagher, Melinda Vonkungthong, Anne Hurley-Bacon, Jasmina Luczo, James Doster, and Charles Foley for technical assistance with this work.

Severe acute respiratory syndrome coronavirus 2, isolate USA-WA1/2020, NR-52281 was deposited by the Centers for Disease Control and Prevention and obtained through BEI Resources, NIAID, NIH. Middle East respiratory syndrome coronavirus, Florida/USA-2_Saudi Arabia_2014, NR-50415 was obtained through BEI Resources, NIAID, NIH. Vero African green monkey kidney cells (ATCC CCL-81), FR-243, were obtained through the International Reagent Resource, Influenza Division, WHO Collaborating Center for Surveillance, Epidemiology and Control of Influenza, Centers for Disease Control and Prevention, Atlanta, GA, USA.

This work was supported by USDA-Agricultural Research Service (project no. 6040-32000-066-00-D).

About the Author

Dr. Suarez is the research leader for the Exotic and Emerging Avian Viral Disease Research Unit of the Agricultural Research Service, USDA. His primary research interests are in the understanding and control of avian influenza and Newcastle disease viruses in poultry and other emerging viral diseases that threaten the poultry industry.

References

- Corman VM, Muth D, Niemeyer D, Drosten C. Hosts and sources of endemic human coronaviruses. *Adv Virus Res.* 2018;100:163–88. <https://doi.org/10.1016/bs.aivir.2018.01.001>
- Chan JF, Kok KH, Zhu Z, Chu H, To KK, Yuan S, et al. Genomic characterization of the 2019 novel human-pathogenic coronavirus isolated from a patient with atypical pneumonia after visiting Wuhan. *Emerg Microbes Infect.* 2020;9:221–36. <https://doi.org/10.1080/22221751.2020.1719902>
- Schlottau K, Rissmann M, Graaf A, Schön J, Sehl J, Wylezich C, et al. SARS-CoV-2 in fruit bats, ferrets, pigs, and chickens: an experimental transmission study. *Lancet Microbe.* 2020;1:e218–e225. [https://doi.org/10.1016/S2666-5247\(20\)30089-6](https://doi.org/10.1016/S2666-5247(20)30089-6)
- Shi J, Wen Z, Zhong G, Yang H, Wang C, Huang B, et al. Susceptibility of ferrets, cats, dogs, and other domesticated animals to SARS-coronavirus 2. *Science.* 2020;368:1016–20. <https://doi.org/10.1126/science.abb7015>
- The Lancet. MERS-CoV: a global challenge. *Lancet.* 2013; 381:1960. [https://doi.org/10.1016/S0140-6736\(13\)61184-8](https://doi.org/10.1016/S0140-6736(13)61184-8)
- Hui DS, Azhar EI, Memish ZA, Zumla A. Human coronavirus infections—severe acute respiratory syndrome (SARS), Middle East respiratory syndrome (MERS), and SARS-CoV-2. Reference Module in Biomedical Sciences. 2020 [cited 2020 Sep 23]. <https://doi.org/10.1016/B978-0-12-801238-3.11634-4>
- Ferguson NM, Van Kerkhove MD. Identification of MERS-CoV in dromedary camels. *Lancet Infect Dis.* 2014;14:93–4. [https://doi.org/10.1016/S1473-3099\(13\)70691-1](https://doi.org/10.1016/S1473-3099(13)70691-1)
- Kandeil A, Gomaa M, Shehata M, El-Taweel A, Kayed AE, Abiadh A, et al. Middle East respiratory syndrome coronavirus infection in non-camelid domestic mammals. *Emerg Microbes Infect.* 2019;8:103–8. <https://doi.org/10.1080/22221751.2018.1560235>
- Hemida MG, Perera RA, Wang P, Alhammadi MA, Siu LY, Li M, et al. Middle East respiratory syndrome (MERS) coronavirus seroprevalence in domestic livestock in Saudi Arabia, 2010 to 2013. *Euro Surveill.* 2013;18:20659. <https://doi.org/10.2807/1560-7917.ES2013.18.50.20659>
- Barr IG, Rynehart C, Whitney P, Druce J. SARS-CoV-2 does not replicate in embryonated hen's eggs or in MDCK cell lines. *Euro Surveill.* 2020;25. <https://doi.org/10.2807/1560-7917.ES.2020.25.25.2001122>

Address for correspondence: Erica Spackman, US National Poultry Research Center, USDA Agricultural Research Service, 934 Station Rd, Athens, GA 30605, USA; email: erica.spackman@usda.gov

Serologic Responses in Healthy Adult with SARS-CoV-2 Reinfection, Hong Kong, August 2020

Paul K.S. Chan, Grace Lui, Asmaa Hachim, Ronald L.W. Ko, Siaw S. Boon, Timothy Li, Niloufar Kavian, Fion Luk, Zigui Chen, Emily M. Yau, Kin H. Chan, Chi-hang Tsang, Samuel M.S. Cheng, Daniel K.W. Chu, Ranawaka A.P.M. Perera, Wendy C.S. Ho, Apple C.M. Yeung, Chit Chow, Leo L.M. Poon, Sophie A. Valkenburg, David S.C. Hui, Malik Peiris

Author affiliations: The Chinese University of Hong Kong, Hong Kong, China (P.K.S. Chan, G. Lui, S.S. Boon, T. Li, F. Luk, Z. Chen, W.C.S. Ho, A.C.M. Yeung, C. Chow, D.S.C. Hui); The University of Hong Kong, Hong Kong (A. Hachim, R.L.W. Ko, N. Kavian, E.M. Yau, K.H. Chan, C. Tsang, S.M.S. Cheng, D.K.W. Chu, R.A.P.M. Perera, L.L.M. Poon, S.A. Valkenburg, M. Peiris)

DOI: <https://doi.org/10.3201/eid2612.203833>

In March 2020, mild signs and symptoms of coronavirus disease developed in a healthy 33-year-old man in Hong Kong. His first infection did not produce virus neutralizing antibodies. In August, he had asymptomatic reinfection, suggesting that persons without a robust neutralizing antibody response might be at risk for reinfection.

response suggests that antibody against SARS-CoV-2 developed on reinfection.

Levels of adaptive cytokine interleukin-2 were elevated on days 10 and 43 (Appendix Figure 3, panels A, B). Reinfection coincided with a stronger interleukin-21 memory type response on day 148 than on days 10 and 43.

Previous studies show that most patients with mild, severe, or asymptomatic SARS-CoV-2 infection produce neutralizing antibodies and antibodies against spike RBD and N proteins (3,4). This case was unusual because the patient had low or undetectable levels of neutralizing and binding antibodies against multiple viral proteins during his primary infection and acute stage of asymptomatic reinfection. He was not immunodeficient because he had IgG against measles and varicella zoster viruses and no history of recurrent infections. The virus from the first infection had a truncation in the 58AA open reading frame 8 gene, which mediates immune evasion through downregulation of major histocompatibility complex and interferon responses (Y. Zhang et al., unpub. data, <https://www.biorxiv.org/content/10.1101/2020.05.24.111823v1>) (8). However, it is unclear if this mutation contributed to the patient's lack of antibody production.

Reasons for this patient's unusual response need to be further investigated. He recovered from his primary infection within 3 weeks, and his secondary infection was asymptomatic. These findings indicate that, in the absence of primary neutralizing antibodies, T cells and mucosal immunity might have played a critical role in resolving the infection. Given the unusual antibody response in this patient to his first infection, researchers must be cautious about generalizing more widely from this patient's experience.

Acknowledgments

We thank Rity Wong, Vickie Li, Miu Ling Chin, Barry Wong, and Kitty Fung for their assistance in this study.

The study was supported by the Health and Medical Research Fund—Commissioned Research on the Novel Coronavirus Disease (COVID-19) (reference nos. COVID190107, COVID190126, COVID190205, and COVID190115) from the Food and Health Bureau, Hong Kong Special Administrative Region Government; and the US National Institutes of Health (contract no. HHSN272201400006C).

About the Author

Prof. Chan is a clinical virologist at the Chinese University of Hong Kong, Hong Kong. His research interests include diagnostics, epidemiology, and pathogenesis.

References

1. Kiyuka PK, Agoti CN, Munywoki PK, Njeru R, Bett A, Otiemo JR, et al. Human coronavirus NL63 molecular epidemiology and evolutionary patterns in rural coastal Kenya. *J Infect Dis*. 2018;217:1728–39. <https://doi.org/10.1093/infdis/jiy098>
2. Callow KA. Effect of specific humoral immunity and some non-specific factors on resistance of volunteers to respiratory coronavirus infection. *J Hyg (Lond)*. 1985;95:173–89. <https://doi.org/10.1017/S0022172400062410>
3. Perera RA, Mok CK, Tsang OT, Lv H, Ko RL, Wu NC, et al. Serological assays for severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), March 2020. *Euro Surveill*. 2020;25:2000421. <https://doi.org/10.2807/1560-7917.ES.2020.25.16.2000421>
4. Hachim A, Kaviani N, Cohen CA, Chin AWH, Chu DKW, Mok CKP, et al. ORF8 and ORF3b antibodies are accurate serological markers of early and late SARS-CoV-2 infection. [Erratum in: *Nat Immunol*. 2020 Aug 27; Epub ahead of print]. *Nat Immunol*. 2020 Aug 17 [Epub ahead of print].
5. Addetia A, Crawford KHD, Dingens A, Zhu H, Roychoudhury P, Huang ML, et al. Neutralizing antibodies correlate with protection from SARS-CoV-2 in humans during a fishery vessel outbreak with high attack rate. *J Clin Microbiol*. 2020;Aug 21;JCM.02107-20. <https://doi.org/10.1128/JCM.02107-20>
6. To KK, Hung IF, Ip JD, Chu AW, Chan WM, Tam AR, et al. COVID-19 re-infection by a phylogenetically distinct SARS-coronavirus-2 strain confirmed by whole genome sequencing. *Clin Infect Dis*. 2020 Aug 25 [Epub ahead of print]. <https://doi.org/10.1093/cid/ciaa1275>
7. Tan CW, Chia WN, Qin X, Liu P, Chen MI, Tiu C, et al. A SARS-CoV-2 surrogate virus neutralization test based on antibody-mediated blockage of ACE2-spike protein-protein interaction. *Nat Biotechnol*. 2020;38:1073–8. <https://doi.org/10.1038/s41587-020-0631-z>
8. Li JY, Liao CH, Wang Q, Tan YJ, Luo R, Qiu Y, et al. The ORF6, ORF8 and nucleocapsid proteins of SARS-CoV-2 inhibit type I interferon signaling pathway. *Virus Res*. 2020;286:198074. <https://doi.org/10.1016/j.virusres.2020.198074>

Address for correspondence: Malik Peiris, School of Public Health, Li Ka Shing Faculty of Medicine, The University of Hong Kong, No. 7 Sassoon Rd., Pokfulam, Hong Kong, China; email: malik@hku.hk; Grace Lui, Department of Medicine and Therapeutics, Faculty of Medicine, The Chinese University of Hong Kong, Prince of Wales Hospital, 30-32 Ngan Shing St., Shatin, New Territories, Hong Kong, China; email: gracelui@cuhk.edu.hk

Serologic Responses in Healthy Adult with SARS-CoV-2 Reinfection, Hong Kong, August, 2020

Appendix

Methods

Patient Follow-Up

Written, informed consent was obtained from the patient to participate in our study on COVID-19, which was approved by The Joint Chinese University of Hong Kong-New Territories East Cluster Research Ethics Committee.

Plaque Reduction Neutralization Test (PRNT)

PRNT antibodies were detected as previously described (1). Briefly, serial dilutions of each serum sample were incubated with 30–40 plaque-forming units of viruses for 1 h at 37°C. The virus–serum mixtures were added onto pre-formed Vero E6 cell monolayers and incubated for 1 h at 37°C in 5% CO₂ incubator. The cell monolayer was then overlaid with 1% agarose in cell culture medium. After 3 d of incubation, the plates were fixed and stained. Antibody titers were defined as the highest serum dilution that resulted in $\geq 50\%$ (PRNT₅₀) reduction in the number of virus plaques.

Surrogate Virus Neutralization Assay

Neutralizing antibodies were also tested by the SARS-CoV-2 surrogate virus neutralization test kits (GeneScript USA, Inc, New Jersey) according to the manufacturer's instructions (2). Briefly, the test sera (60 μ L), the positive and negative controls were diluted at 1:10 and mixed with an equal volume of horseradish peroxidase (HRP) conjugated SARS-CoV-2 spike receptor binding domain (RBD) protein and incubated for 30 min at 37°C. Then, 100 μ L of each mix was added to the wells on the microtiter plate coated with ACE-2 receptor, the plate was sealed and incubated at 37°C for 15 min. The plates were then washed with wash-solution,

tapped dry and 100 μ L of 3,3',5,5'-Tetramethylbenzidine (TMB) solution was added to each well and incubated in the dark at room temperature for 15 min. The reaction was stopped by addition of 50 μ L of Stop Solution to each well and the absorbance read at 450 nm in an ELISA reader. Assuming the positive and negative controls gave the recommended OD₄₅₀ values, the % inhibition of each serum was calculated as $(1 - \text{OD value of the sample} / \text{OD value of the negative control}) \times 100$. An inhibition of $\geq 20\%$ is regarded as a positive result while that $< 20\%$ is negative (2).

Luciferase Immunoprecipitation (LIPS) Assay

The LIPS assay was initially described by Burbelo et al. (3) adapted to SARS-CoV-2 by us as previously described (4). Briefly, Renilla luciferase tagged SARS-CoV-2 N antigens were produced from COS1 cells, and antigen equalized to 10^7 luciferase units for each serological test. Serum (heat inactivated and diluted 1:100 in Buffer A (50 mM Tris, pH 7.5, 100 mM NaCl, 5 mM MgCl₂, 1% Triton X-100)) was incubated with 10^7 LU of (Ruc)-N antigen for 1 h with shaking at 800 rpm. Ultralink protein A/G beads were added to the (Ruc)-antigen and serum mixture in a 96-deep-well polypropylene microtiter plate and incubated for 1 h with shaking at 800 rpm. The entire volume was then transferred into HTS plates and washed 10 times with Buffer A, and then twice with PBS. The plate was read using QUANTI-Luc Gold substrate (Invivogen, USA) as per manufacturer's instructions on a Wallac MicroBeta JET luminometer 1450 LSC & Luminescence counter and its software for analysis (PerkinElmer, USA). Experimental controls include no-serum blank wells with (Ruc)-antigens and negative control serum from age-matched noninfected patient plasma collected prior to the COVID-19 pandemic ($n = 20$). The background corresponds to the LU signal from each Ruc-fusion antigen with protein A/G and substrate with no serum. The cutoff limits were derived from the mean value plus $3 \times \text{SD}$ of the negative controls.

Virus Full-Genome Sequencing

We used the methods previously described by us (5). Briefly, virus genome was reverse transcribed with multiple gene-specific primers targeting different regions of the viral genome. The synthesized cDNA was then subjected to multiple overlapping 2-kb PCRs for full-genome amplification. PCR amplicons obtained from the same specimen were pooled and sequenced using MiSeq sequencing platform (Illumina). Sequencing library was prepared by Nextera XT

DNA library prep Kit (Illumina) following standard protocol. Generated sequencing reads were mapped to a reference virus genome by BWA (6), and genome consensus was generated by Geneious version 11.1.4 (<https://www.geneious.com>).

Anti-SARS-CoV-2 N IgG by In-House Indirect Microtiter Plate ELISA

Purified glutathione S transferase (GST)-tagged full-length nucleocapsid fusion protein (GST-N) of SARS-CoV-2 (1 µg/mL) was coated onto Immulon 2 HB 96-well microtiter plate (ImmunoChemistry, USA) in bicarbonate buffer (pH 9.6) overnight at 4°C. Blocking buffer containing 0.25% BSA (Sigma, USA) in 1 × TBS was added into wells, followed by adding 100 µL of human plasma or serum diluted at 1:100 in 1 × TBS containing 0.2% Tween-20 at 37°C for 1 h. The plates were washed and incubated with horse-peroxidase-labelled goat antihuman IgG (Invitrogen, USA) at room temperature for 30 min. After washing, detection was carried out by adding 3,3',5,5'-Tetramethylbenzidine (TMB) substrate (Sigma, USA) in dark and the reaction was stopped by adding 2 M of sulfuric acid. The results were read at 450 nm using a VICTOR 3 Multilabel Plate Reader (PerkinElmer, USA). Mean OD of negative controls plus 3 standard deviations was defined as cut-off for reactive samples. Validation using 50 convalescent samples of patients with confirmed SARS-CoV-2 infection collected at ≥ 30 days from illness onset revealed 100% sensitivity, and from 50 samples taken from healthy persons before November 2019 revealed 100% specificity.

IgG Against Varicella Zoster Virus and Measles by Commercial Microtiter Plate ELISA

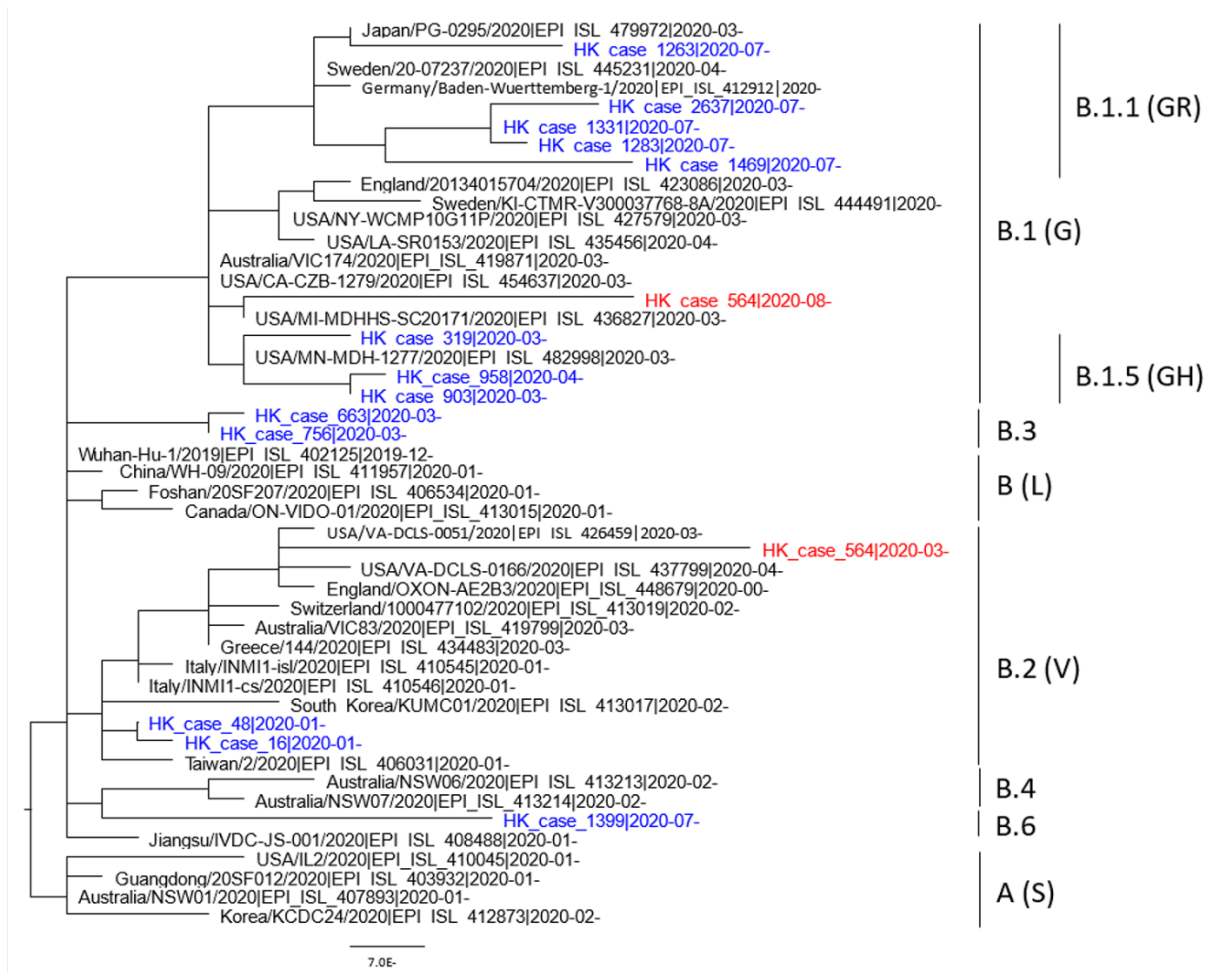
Commercial assays for measles IgG and varicella zoster virus IgG (Trinity Biotech, USA) were used according to the manufacturer's instructions. OD index of ≥ 1.1 is regarded as positive in both assays. The serum sample collected at Day-10 from this patient was positive for varicella zoster virus IgG (OD: 6.358) and measles IgG (OD: 2.553).

Cytokine Bead Array

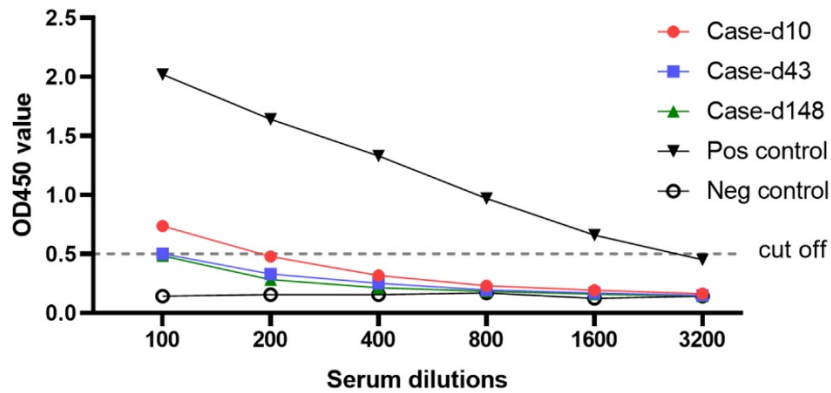
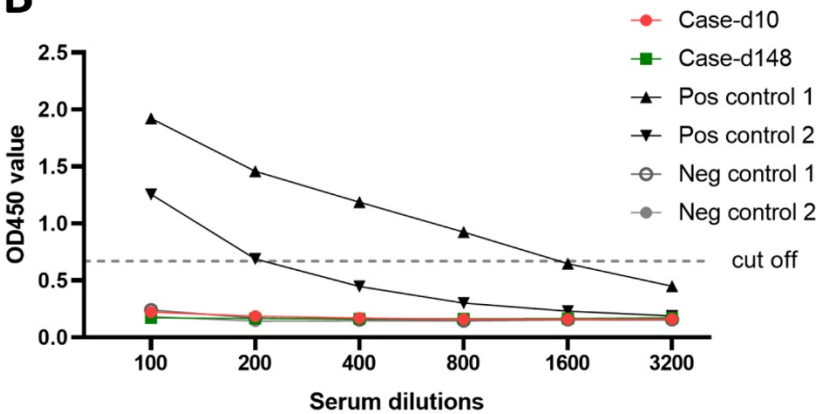
A custom 10 cytokines LegendPlex (Biolegend, USA) panel which included CCL3 (MIP-1 α), IFN- α 2, IFN- γ , IL-2, IL-4, IL-5, IL-9, IL-10, IL-13, and IL-21 was used according to the manufacturer's instructions. Samples were acquired by flow cytometry on a FACS Attune (Invitrogen) and analyzed with LegendPlex software as per manufacturer's instructions. Samples included case 564 (day 10, 43 and 148, and negative controls (healthy donors, pre-pandemic, no current infection, n=7). Patient sera and controls were run in parallel on the same occasion.

References

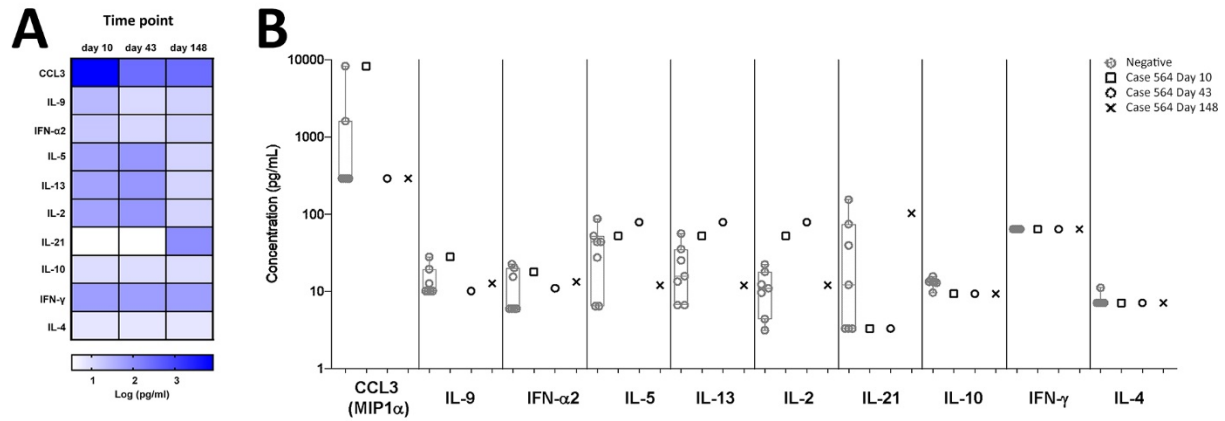
1. Perera RA, Mok CK, Tsang OT, Lv H, Ko RL, Wu NC, et al. Serological assays for severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), March 2020. *Euro Surveill.* 2020;25:2000421. [PubMed https://doi.org/10.2807/1560-7917.ES.2020.25.16.2000421](https://doi.org/10.2807/1560-7917.ES.2020.25.16.2000421)
2. Tan CW, Chia WN, Qin X, Liu P, Chen MI, Tiu C, et al. A SARS-CoV-2 surrogate virus neutralization test based on antibody-mediated blockage of ACE2-spike protein-protein interaction. *Nat Biotechnol.* 2020;38:1073–8. [PubMed https://doi.org/10.1038/s41587-020-0631-z](https://doi.org/10.1038/s41587-020-0631-z)
3. Burbelo PD, Ching KH, Klimavicz CM, Iadarola MJ. Antibody profiling by Luciferase Immunoprecipitation Systems (LIPS). *J Vis Exp.* 2009; 32:1549. [PubMed https://doi.org/10.3791/1549](https://doi.org/10.3791/1549)
4. Hachim A, Kavian N, Cohen CA, Chin AWH, Chu DKW, Mok CKP, et al. ORF8 and ORF3b antibodies are accurate serological markers of early and late SARS-CoV-2 infection. [Erratum in: *Nat Immunol.* 2020 Aug 17; Epub ahead of print.] *Nat Immunol.* 2020 Aug 17 [Epub ahead of print]. [PubMed https://doi.org/10.1038/s41587-020-0631-z](https://doi.org/10.1038/s41587-020-0631-z)
5. Sit THC, Brackman CJ, Ip SM, Tam KWS, Law PYT, To EMW, et al. Infection of dogs with SARS-CoV-2. *Nature.* 2020 May 14 [Epub ahead of print]. <https://doi.org/10.1038/s41586-020-2334-5> PMID: 32408337
6. Li H, Durbin R. Fast and accurate short read alignment with Burrows-Wheeler transform. *Bioinformatics.* 2009;25:1754–60. [PubMed https://doi.org/10.1093/bioinformatics/btp324](https://doi.org/10.1093/bioinformatics/btp324)



Appendix Figure 1. Phylogenetic tree of selected severe acute respiratory syndrome coronavirus 2 isolates. Red indicates viruses isolated from patient 564, Hong Kong, 2020. Patient 564 was sampled during his first infection in March and the second infection in August. Blue indicates viruses from other recent Hong Kong cases. Phylogenetic tree constructed using PhyML. Symptom onset date (YYYY-MM-DD) and GISAID access no. of the reference genomes are shown in virus taxa. Virus lineages are indicated.

A**B**

Appendix Figure 2. Serum IgG and IgM responses to spike receptor binding domain in patient with selected severe acute respiratory syndrome coronavirus 2 reinfection, Hong Kong, 2020. Serial dilutions of serum samples from the patient were tested in ELISA selective for IgG (A) and IgM (B) against SARS-CoV-2 receptor binding domain. Positive and negative control serum samples included for comparison. The dotted line represents the cut-off in the previously validated assay (1).



Appendix Figure 3. Pro- and antiinflammatory cytokines and chemokines measured by cytokine bead array in a patient with severe acute respiratory syndrome coronavirus 2 reinfection, Hong Kong, 2020. (A) Cytokine and chemokine levels in patient on days 10, 43, and 148 after symptom onset. (B) The patient's response at different time points (black symbols) were compared to those of 7 negative controls (open gray circles). Data represent individual responses. Box plots show interquartile ranges. IFN, interferon; IL, interleukin; CCL3, chemokine (C-C motif) ligand 3; MIP-1 α , macrophage inflammatory protein-1 α .