

COVID-19 in solid organ transplant: A multi-center cohort study

Olivia S. Kates MD¹, Brandy M Haydel CCRC², Sander S Florman MD², Meenakshi M Rana MD³, Zohra S Chaudhry MD⁴, Mayur S Ramesh MD⁴, Kassem Safa MD⁵, Camille Nelson Kotton MD⁶, Emily A Blumberg MD⁷, Behdad D Besharatian MD⁷, Sajal D Tanna MD⁸, Michael G Ison MD^{8,9}, Maricar Malinis MD¹⁰, Marwan M Azar MD¹⁰, Robert M Rakita MD¹, Jose A Morillas MD¹¹, Aneela Majeed MD¹¹, Afrah S Sait MD¹², Mario Spaggiari MD¹³, Vagish Hemmige MD¹⁴, Sapna A Mehta MD¹⁵, Henry Neumann MD¹⁵, Abbasali Badami MD¹⁶, Jason D Goldman MD, MPH^{1,17}, Anuradha Lala MD¹⁸, Marion Hemmersbach-Miller MD, PhD¹⁹, Margaret E McCort MD¹⁴, Valida Bajrovic MD²⁰, Carlos Ortiz-Bautista MD²¹, Rachel Friedman-Moraco MD²², Sameep Sehgal MD²³, Erika D Lease MD²⁴, UW COVID-19 SOT Study Team[#],
Cynthia E Fisher MD, MPH^{1,*}, and Ajit P Limaye MD^{1,*}

1. Division of Allergy and Infectious Diseases, University of Washington, Seattle, WA, USA
2. Recanati/Miller Transplantation Institute, Icahn School of Medicine at Mount Sinai, New York, NY, USA
3. Division of Infectious Diseases, Department of Medicine, Icahn School of Medicine at Mount Sinai, New York, NY, USA
4. Transplantation Infectious Diseases and Immunotherapy, Henry Ford Health System, Detroit, MI, USA
5. Transplant Center and Division of Nephrology, Massachusetts General Hospital, Boston, MA, USA
6. Transplant Infectious Diseases, Massachusetts General Hospital, Boston, MA, USA
7. Department of Medicine, Perelman School of Medicine University of Pennsylvania, Philadelphia, PA, USA
8. Division of Infectious Diseases, Northwestern University Feinberg School of Medicine, Chicago, IL, USA

9. Division of Organ Transplantation, Northwestern University Feinberg School of Medicine, Chicago, IL, USA
10. Section of Infectious Diseases, Department of Internal Medicine, Yale-New Haven Hospital, New Haven, CT, USA
11. Department of Infectious Diseases, Cleveland Clinic, Cleveland, OH, USA
12. Division of Infectious Diseases, Department of Medicine, Johns Hopkins School of Medicine, Baltimore, Maryland, USA
13. Division of Transplantation, University of Illinois at Chicago, Chicago, IL, USA
14. Montefiore Medical Center, Bronx, NY, USA
15. NYU Langone Transplant Institute, New York, NY, USA
16. SUNY Downstate Health Sciences University, Brooklyn, NY, USA
17. Swedish Center for Research and Innovation, Swedish Medical Center, Seattle, WA, USA
18. Division of Cardiology, Department of Medicine, Icahn School of Medicine at Mount Sinai, New York, NY, USA
19. Section of Infectious Diseases Baylor College of Medicine, Houston, TX, USA
20. Division of Infectious Disease, Department of Medicine, University of Colorado, Aurora, CO, USA
21. Hospital Universitario Gregorio Marañón, CIBERCV, Madrid, Spain
22. Division of Infectious Diseases, Department of Medicine, Emory University, Atlanta, GA, USA
23. Department of Thoracic Medicine And Surgery, Temple University, Philadelphia, PA, USA
24. Division of Pulmonary, Critical Care, and Sleep Medicine, University of Washington, Seattle, WA, USA

*Cynthia E Fisher MD and Ajit P Limaye MD contributed equally to this manuscript.

Keywords: COVID-19, SARS-CoV-2, coronavirus, transplantation, solid organ transplantation

Summary: In this analysis of 482 solid organ transplant recipients with COVID-19, the authors report 28-day mortality of 20.5% among inpatients, strongly associated with age and comorbidities, and conclude that this is comparable to rates observed in the general population.

Correspondence:

Ajit P. Limaye, M.D.

Professor of Medicine

University of Washington

1959 N.E. Pacific St.

Seattle, WA 98195-6174

TEL: +1 206 598 1041

Alternate Corresponding Author:

Cynthia E. Fisher, M.D.

Associate Professor of Medicine

University of Washington

1959 N.E. Pacific St.

Seattle, WA 98195-6174

TEL: +1 206 598 9149

ABSTRACT

Background

The COVID-19 pandemic has led to significant reductions in transplantation, motivated in part by concerns of disproportionately more severe disease among solid organ transplant (SOT) recipients. However, clinical features, outcomes, and predictors of mortality in SOT recipients are not well-described.

Methods

We performed a multi-center cohort study of SOT recipients with laboratory-confirmed COVID-19. Data were collected using standardized intake and 28-day follow-up electronic case report forms. Multivariable logistic regression was used to identify risk factors for the primary endpoint, 28-day mortality, among hospitalized patients.

Results

Four hundred eighty-two SOT recipients from >50 transplant centers were included: 318 (66%) kidney or kidney/pancreas, 73 (15.1%) liver, 57 (11.8%) heart, and 30 (6.2%) lung. Median age was 58 (IQR 46-57), median time post-transplant was 5 years (IQR 2-10), 61% were male, and 92% had ≥ 1 underlying comorbidity. Among those hospitalized (376 [78%]), 117 (31%) required mechanical ventilation, and 77 (20.5%) died by 28 days after diagnosis. Specific underlying comorbidities (age >65 [aOR 3.0, 95%CI 1.7-5.5, $p < 0.001$], congestive heart failure [aOR 3.2, 95%CI 1.4-7.0, $p = 0.004$], chronic lung disease [aOR 2.5, 95%CI 1.2-5.2, $p = 0.018$], obesity [aOR 1.9, 95% CI 1.0-3.4, $p = 0.039$]) and presenting findings (lymphopenia [aOR 1.9, 95%CI 1.1-3.5, $p = 0.033$], abnormal chest imaging [aOR 2.9, 95%CI 1.1-7.5, $p = 0.027$]) were independently associated with mortality. Multiple measures of immunosuppression intensity were not associated with mortality.

Conclusions

Mortality among SOT recipients hospitalized for COVID-19 was 20.5%. Age and underlying comorbidities rather than immunosuppression intensity-related measures were major drivers of mortality.

Introduction

The COVID-19 pandemic has affected over 10 million people, with over 500,000 deaths worldwide. Estimated mortality rates among those hospitalized with COVID-19 vary widely and have been associated with advanced age and comorbidities in the general population; however, less is known about outcomes of COVID-19 in solid organ transplant (SOT) recipients.¹⁻³ Based on experience with other respiratory viruses in immunocompromised populations, there has been concern about a disproportionately severe impact of COVID-19 in SOT recipients related to immunosuppression.^{4,5} However, because of the unique contribution of a dysregulated and exaggerated immune response in COVID-19 morbidity and mortality, there has also been discussion of a possible favorable effect of immunosuppression in SOT recipients who develop COVID-19.⁶ Concerns about unfavorable outcomes, along with other issues such as infection control and resource availability, have led to changes in immunosuppression management and a substantial decrease or even temporary discontinuation of transplants at many centers around the world. As of 11 April 2020, the overall rate of deceased donor organ transplantation had fallen by 51% in the United States, by 87% in Spain, and by 91% in France.⁷

The clinical aspects and impact of COVID-19 in SOT recipients remain uncertain. Early results have varied, with mortality rates ranging from 7.1% to as high as 53% in one small series.^{8,9} These studies had important limitations including small size, single-center or limited geographic locale, or limited follow-up.⁸⁻²¹ More precise estimates of morbidity and mortality of COVID-19 in SOT, identification of risk factors for mortality, and comparison to general populations are critical for two main purposes: 1) to better understand the impact of transplant-related immunosuppression on outcomes of COVID-19, and 2) to inform transplant program practices in the COVID-19 era and in the event of resurgence of the epidemic.

We report the results of a large, prospective, multi-center study of SOT recipients with COVID-19, all of whom were followed for 28 days, using standardized data collection tools, to assess patient characteristics, clinical presentation, outcomes, and risk factors for mortality.

Methods

Study Oversight

The study was approved by the University of Washington Institutional Review Board with waiver of informed consent. The Institutional Review Board issued a “not human subjects research” designation for contributors reporting de-identified data accessed during routine clinical care. Study sites underwent review by local institutional review boards if needed to access data outside of routine care, or to maintain a key to identify patient records, at their discretion.

Study Design

This multi-site prospective cohort study included recipients of any SOT with laboratory-confirmed COVID-19 by polymerase chain reaction of an upper or lower respiratory sample. Study data were collected using the secure, web-based data capture software program REDCap (Research Electronic Data Capture), hosted at the University of Washington.^{22,23} The standardized electronic case report form included only de-identified patient data. The initial component collected patient demographics, baseline comorbidities, transplant-related history, presenting symptoms, focused laboratory values, and imaging. The follow-up component included hospital and ICU admission, mechanical ventilation, death and time to death, complications, and management strategies. Table S1 describes all variables collected. Potential contributors were notified of the study through message boards hosted by the American Society of Transplantation, the American Society of Transplant Surgeons, and the International Society for Heart and Lung Transplantation. The study period included reports received March 7 to May

13 for cases diagnosed from March 1, 2020 - April 15, 2020 to ensure 28-day follow-up for all patients.

Statistical Analyses

Results are presented descriptively in pre-specified subpopulations, including in patients stratified by death by 28 days, hospitalized patients only, and by organ(s) transplanted. The primary outcome was 28-day mortality in the subset of patients hospitalized after COVID diagnosis. We summarized published studies of COVID-19 in hospitalized SOT and general populations as of June 19, 2020, and calculated pooled weighted estimates of mortality and baseline comorbidities. Studies of SOT recipients that included ≥ 10 patients and outcomes of patients hospitalized with COVID-19 were considered for inclusion. The association between baseline covariates and death was assessed in univariate and multivariable analyses using logistic regression for both the subset hospitalized after COVID diagnosis and among the full cohort. We assessed all collected variables, and those that either had a $p < 0.1$ in univariate analysis or that were considered important based on results of previous studies, and for which there were adequate events to allow for meaningful analysis, were considered for the multivariable model. Stepwise regression was used to inform the final model and potential interactions among covariates were assessed. Complete data were available for the majority of variables; missing data were handled via multiple imputation using the multivariate by chained equations method.²³ The final multivariable logistic regression model included age; gender; mTOR-containing maintenance immunosuppression regimen, baseline comorbidities (congestive heart failure [CHF], chronic lung disease, diabetes mellitus, obesity) individually or in combination; initial absolute lymphocyte count; and evidence of pneumonia on initial chest imaging. Both age and absolute lymphocyte count were assessed as dichotomous variables (age ≤ 65 vs > 65 years, lymphocytes < 0.5 vs $\geq 0.5 \times 10^9/L$), based on clinical relevance and previously published studies, and after analyzing the effects as continuous variables and as

multiple discrete strata. Although there are no defined well-validated measures of immunosuppression intensity, we assessed the following as potential surrogates, in accordance with prior studies: earlier time post-transplant, thoracic (lung or heart) compared to non-thoracic organ transplant, receipt of augmented immunosuppression within three months of COVID-19 diagnosis, or a higher number of baseline maintenance immunosuppressive agents.^{10,11,16,25} Number of maintenance immunosuppressive agents was assessed by comparing those on 2 immunosuppressants and those on 3 or more immunosuppressants to those receiving 0 or 1 immunosuppressants at baseline as a reference, considering all immunosuppressants and separately considering only the most commonly used immunosuppressants (calcineurin inhibitors, anti-metabolites, and steroids). All analyses were performed using Stata version 13.1 (Stata Corporation, College Station, Texas).

Results

Study population.

A total of 538 cases were submitted between March 7 and May 14 2020; 56 were excluded, leaving 482 in the final study population. Reasons for exclusion were: No confirmed COVID-19 diagnosis (n=6), duplicate reports (n=6), reports missing >10% of requested data (n=4), reports submitted with less than 28 days of follow-up (n=18), and cases previously published as of the date of data extraction (n=21). One report was withdrawn by the contributor. (Consort diagram; Supplemental Figure 1)

Baseline characteristics of the study population

Baseline characteristics of the complete study population and stratified by vital status on day 28 are shown in Table 1. The overall study population included patients with mostly community-acquired infection (83%), from a range of geographic locales, and included a small proportion of lung transplant recipients (~6%) and recent transplant recipients (~6%). Most were receiving

calcineurin inhibitor-based maintenance immunosuppression (91%). A high proportion had at least one of the underlying comorbidities listed in Table 1 (445 [92.3%] overall, and 97% of kidney, 78% of liver, 87% of heart, and 86.7% of lung recipients).

Summary of clinical outcomes.

Seventy-eight percent of the cohort was hospitalized for COVID-19. A small number were already hospitalized for another indication at the time of diagnosis (6.4%), and the remainder (16%) were managed on an outpatient basis. Of patients hospitalized due to COVID-19, 147 (39%) required ICU care and 117 (31%) required mechanical ventilation. The mortality rate by day 28 after COVID-19 diagnosis among the overall cohort was 90 of 482 (18.7%), and 77 of 376 (20.5%) among those hospitalized. A summary of clinical outcomes is shown in Table 2 for the entire cohort and for the subset hospitalized due to COVID-19. Table S2 shows the baseline characteristics and outcomes stratified by organ type transplanted.

Unadjusted Kaplan Meier analyses of mortality by day 28 after diagnosis, separately for all patients and the hospitalized subset, by specific organ transplant type, and by thoracic (heart or lung) versus non-thoracic organ transplant, are shown in Figure 1. For the majority of subsets assessed, mortality appeared to stabilize by the end of the 28-day follow-up.

Risk factors for mortality

Risk factors for mortality were analyzed among the subset of patients hospitalized with COVID-19, since mortality occurred primarily in this group and because comparator studies in general populations focus on this subset (Table 3). Age >65, CHF, chronic lung disease, and obesity, rather than all comorbidities assessed, were the baseline factors independently associated with mortality by 28 days. These comorbidities were common: the proportions with 1, or ≥ 2 were 200 (42.3%) and 84 (17.8%), respectively. Rates of these baseline comorbidities were similar

among the different organ transplant groups except for lung recipients, in whom 9 (32%) had 2 or more of these comorbidities. When these specific comorbidities were assessed in combination in multivariable analysis (omitting the individual components), the strength of the association with mortality was higher with a greater number of comorbidities: 1 vs 0, aOR 3.0 (95%CI: 1.4-6.3), ≥ 2 vs. 0, aOR 11.0 (95%CI: 5.0-24.0), suggesting a cumulative effect of baseline comorbidities on mortality. Race, ethnicity, and male gender were not associated with mortality. Presence of pneumonia at baseline (assessed by abnormal chest imaging) and lymphopenia (<0.5 thousand/mL) were independently associated with mortality. Qualitatively and quantitatively similar results were seen in the overall cohort for all of these analyses (data not shown).

We explored multiple potential surrogates of immunosuppression intensity (earlier time post-transplant, thoracic [lung, heart] compared to non-thoracic organ transplant, or receipt of augmented immunosuppression within three months), and did not find an association of any of these factors with mortality. Results of the analysis between thoracic vs. non-thoracic organs and mortality were similar when thoracic organ was restricted to lung transplant only. We also assessed the association between a higher number of maintenance immunosuppressive agents (0-1 vs 2 and 0-1 vs 3 or more immunosuppressants at baseline) and death in univariate analysis and similarly found no association either when considering all types of maintenance immunosuppression or when restricting analysis to calcineurin inhibitors, antimetabolites, and steroids only. (Table 3)

Interventions and treatments.

The most commonly used intervention was immunosuppression modification in 337 (70%) patients. (Figure 2) In 56% the antimetabolite (mycophenolate or azathioprine) was discontinued, 10% had the antimetabolite reduced, and $<1\%$ had all immunosuppression

discontinued. The most commonly used treatment was chloroquine or hydroxychloroquine, in 296 (61%) patients. QTc prolongation was reported in 13/296 (4.4%). One patient experienced ventricular fibrillation with Torsade de pointes, and one patient developed a junctional arrhythmia. Fourteen (2.9%) patients were treated with remdesivir, 49 (10%) received corticosteroids, and 63 (13%) received an anti-IL6-receptor monoclonal antibody, either tocilizumab (57) or sarilumab (5).

Discussion

In this multicenter cohort study of SOT recipients with COVID-19, the 28-day mortality rate among hospitalized patients was 20.5%. Older age, CHF, chronic lung disease, obesity, lymphopenia, and radiographic abnormalities at presentation were associated with mortality, but transplant-related measures of immunosuppression intensity were not.

The mortality rate of hospitalized patients in the cohort was similar to pooled weighted estimates derived from prior studies (Table S3a)⁸⁻²¹ although these studies were small and heterogeneous. A small proportion of patients (33 [8.7%]) in this cohort remained hospitalized by day 28, so it is possible that the eventual mortality rate may have been slightly higher. Among the underlying comorbidities assessed, CHF, chronic lung disease, and obesity were independently associated with increased mortality. The prevalence of these baseline comorbidities was high, and the magnitude of the association of these comorbidities with mortality was greater with increasing numbers of comorbidities, suggesting cumulative impact. Several previously described comorbidities associated with mortality in general populations (DM, CKD, HTN)^{2,3,26} were not independently associated with mortality in this SOT cohort. Reason(s) for this difference remain uncertain, but might be related to definitions utilized or other differences in populations. Pneumonia at the time of diagnosis, as defined by chest imaging abnormalities, was also associated with mortality among hospitalized patients, as similarly reported in general

population studies.^{27,28} Collectively, these findings are compatible with underlying comorbidities and illness severity at presentation as the major determinants of mortality in SOT recipients. Although there have been concerns about geographic variability in outcomes, an independent association of mortality with geographic location was not identified in this study. Although black and Hispanic patients comprised a higher proportion of this cohort relative to Organ Procurement and Transplantation Network data as of June 4, 2020, we did not observe an association of these factors with mortality. The observational study design precluded assessment of the relationship between various treatments utilized and mortality.

An unexpected finding was the lack of association of correlates of immunosuppression intensity at baseline with increased mortality. Neither earlier time post-transplant, receipt of a thoracic compared to non-thoracic organ transplant, receipt of recent augmented immunosuppression, nor type of maintenance immunosuppression regimen or number of agents was associated with mortality.²⁵ The finding of an apparent lack of association of immunosuppression-related factors on mortality should be interpreted cautiously given the lack of well-defined surrogates for immunosuppression intensity, limited power based on the sample size, and the possibility of confounding. However, this important issue should be explored in future studies, given the importance for predicting risk and/or management of SOT patients with COVID-19.

The potential negative impact of SOT-related immunosuppression on clinical outcomes of COVID-19 has been debated, and few studies have directly compared outcomes in SOT and general populations. The few studies that included multivariable analyses of risk factors for mortality among hospitalized general populations with COVID-19 had variable durations of follow-up (reviewed in Table S3b).^{2,27-31} Mortality estimates ranged from 8-33% in these studies (pooled weighted average, 19.3% [933 of 4831]), and were generally comparable to the mortality among the SOT cohort in the current study. Among general population cohort studies,

the prevalence of baseline comorbidities and median age were also similar to those in the current SOT cohort. Additionally, there was a consistent association of age and underlying comorbidities with increased mortality across general population studies, similar to that found in the present SOT cohort, highlighting the impact of these factors on mortality across different populations. Similarly, in a large population of patients with cancer, age and comorbidities were associated with mortality, but not stage of malignancy or recent treatments including chemotherapy or immunotherapy.³² However, future comparisons between general and immunocompromised populations should include careful adjustment for comorbidities and the use of well-validated mortality risk scores in this setting.

There are several implications of our findings. First, we identified specific factors (age >65 years, CHF, chronic lung disease, obesity) for COVID-19 mortality in hospitalized SOT recipients, that should facilitate targeting of future studies of prevention or treatment to high-risk SOT populations. SOT is a life-saving and quality of life-improving intervention, and immunosuppression-related factors in this setting did not appear to independently impact mortality. These findings support current Center for Medicare and Medicaid Services recommendations that SOT be considered a grade 3b procedure (i.e. do not delay), even in the setting of widespread COVID-19 activity,³³ as long as other necessary resources to safely perform transplantation and associated care are available. Although similar to the general population, mortality among SOT recipients hospitalized with COVID-19 is very high, and prevention of new infections using evidence-based individual and institutional strategies such as those put forth by the AST will be essential to mitigate the negative effects of this pandemic.³⁴

The strengths of the study include the flexible design, broad multi-center participation, standardized data collection, and standardized 28-day duration of follow-up. We demonstrate the feasibility and importance of a broadly collaborative, multidisciplinary approach to rapidly

develop a dataset to inform on an emerging infectious challenge. We also acknowledge potential limitations. We relied on clinician-reported cases, which may be subject to reporting bias; however, contributors attested that cases were reported consecutively and not selectively. As for all reported prior studies, diagnosis of COVID-19 and subsequent inclusion may be subject to testing bias. We focused on hospitalized patients, and thus these conclusions may not be broadly generalizable to all patients diagnosed and managed in the outpatient setting, particularly as testing practices evolve. The pragmatic study design precluded the collection of extensive laboratory parameters as well as complex clinical risk scores. Future studies should consider the predictive value of clinical risk scores such as the Sequential Organ Failure Assessment (SOFA) in COVID-19 outcomes. Independent verification of all submitted data also was not feasible. Despite follow-up of all patients for 28 days, 33 (8.7%) were still hospitalized, so the total mortality rate might eventually be slightly higher than that reported, and longer-term outcomes were not assessed. The numbers of patients with non-kidney organ transplants and those who were early in the post-transplant period was small, and even though these factors were not associated with mortality in multivariable analysis, this may have been limited by power. Thus, additional studies are needed in non-kidney organ transplant recipients and those who are recently transplanted. The sample size, while substantially larger than previously reported, might not have been large enough to identify less frequent covariates or those with lesser association with mortality.

In summary, among hospitalized SOT recipients with COVID-19 with high rates of underlying medical comorbidities, mortality was similar to that described in the general population and was driven largely by underlying medical comorbidities and certain clinical features at presentation, rather than surrogate measures of immunosuppression intensity. Future studies to better define the attributable effect of immunosuppression on outcomes in SOT recipients are warranted.

Acknowledgments

We are grateful for critical review and comments by Siddhartha Kapnadak MD, and for the assistance of Emma Honeyman BS with manuscript preparation.

The following are the members of the UW COVID-19 SOT Study Team, without whom this work would not have been possible:

Akanksha Arya MD, MBA, Amy Jeng MD, Alexander Kuo MD, Alfred Luk MD, Alfredo G Puing MD, Ana P Rossi MD, MPH, Andrew J Brueckner PharmD, Ashrit Multani MD, Brian C Keller MD, PhD, Darby Derringer PharmD, Diana F Florescu MD, Edward A. Dominguez MD, Elena Sandoval MD, FEBCTS, Erin P Bilgili BS, PharmD, Faris Hashim MD, Fernanda P Silveira MD, MS, Ghady Haidar MD, Hala G Joharji PharmD, Haris F Murad MBBS, Imran Yaseen Gani MD, Jose-Marie el-amm MD, Joseph Kahwaji MD, Joyce Popoola FRCP, PhD, Julie M. Yabu MD, MTM, Kailey Hughes MPH, Kapil K Saharia MD, MPH, Kiran Gajurel MD, Lyndsey J. Bowman PharmD, Massimiliano Veroux MD, PhD, Megan K Morales MD, Monica Fung MD, Nicole M. Theodoropoulos MD, MS, Oveimar de la Cruz MD, Rajan Kapoor MD, Ricardo M. La Hoz MD, Sridhar R Allam MD, MPH, Surabhi B. Vora MD, MPH, Todd P McCarty MD, Tracy Anderson-Haag PharmD, BCPS, Uma Malhotra MD, Ursula M Kelly MD, Vidya Bhandaram MD, William M Bennett, Zurabi Lominadze MD

The authors have no potential conflicts of interests to disclose relating to the present manuscript.

References

1. Center JHCR. COVID-19 Mortality by Country. <https://coronavirus.jhu.edu/data/mortality>. Updated June 6, 2020. Accessed June 7, 2020. In.
2. Imam Z, Odish F, Gill I, et al. Older age and comorbidity are independent mortality predictors in a large cohort of 1305 COVID-19 patients in Michigan, United States. *J Intern Med*. 2020.
3. Zhou F, Yu T, Du R, et al. Clinical course and risk factors for mortality of adult inpatients with COVID-19 in Wuhan, China: a retrospective cohort study. *Lancet*. 2020;395(10229):1054-1062.
4. Kumar D, Michaels MG, Morris MI, et al. Outcomes from pandemic influenza A H1N1 infection in recipients of solid-organ transplants: a multicentre cohort study. *Lancet Infect Dis*. 2010;10(8):521-526.
5. Nam HH, Ison MG. Community-acquired respiratory viruses in solid organ transplant. *Curr Opin Organ Transplant*. 2019;24(4):483-489.
6. Kates OS, Fisher CE, Stankiewicz-Karita HC, et al. Earliest cases of coronavirus disease 2019 (COVID-19) identified in solid organ transplant recipients in the United States. *Am J Transplant*. 2020;20(7):1885-1890. doi:10.1111/ajt.15944
7. Rodrigo E, Miñambres E, Gutiérrez-Baños JL, Valero R, Belmar L, Carlos Ruiz J. COVID-19 related collapse of transplantation systems: a heterogeneous recovery? *Am J Transplant*. 2020.
8. Yi SG, Rogers AW, Saharia A, et al. Early Experience With COVID-19 and Solid Organ Transplantation at a US High-volume Transplant Center. *Transplantation*. 2020.
9. Crespo M, José Pérez-Sáez M, Redondo-Pachón D, et al. COVID-19 in elderly kidney transplant recipients. *Am J Transplant*. 2020.

10. Pereira MR, Mohan S, Cohen DJ, et al. COVID-19 in solid organ transplant recipients: Initial report from the US epicenter. *Am J Transplant.* 2020.
11. Akalin E, Azzi Y, Bartash R, et al. Covid-19 and Kidney Transplantation. *N Engl J Med.* 2020.
12. Latif F, Farr MA, Clerkin KJ, et al. Characteristics and Outcomes of Recipients of Heart Transplant With Coronavirus Disease 2019. *JAMA Cardiol.* 2020.
13. Tschopp J, L'Huillier AG, Mombelli M, et al. First experience of SARS-CoV-2 infections in solid organ transplant recipients in the Swiss Transplant Cohort Study. *Am J Transplant.* 2020.
14. Alberici F, Delbarba E, Manenti C, et al. A single center observational study of the clinical characteristics and short-term outcome of 20 kidney transplant patients admitted for SARS-CoV2 pneumonia. *Kidney Int.* 2020;97(6):1083-1088.
15. Hoek RAS, Manintveld OC, Betjes MGH, et al. Covid-19 in solid organ transplant recipients: A single center experience. *Transpl Int.* 2020.
16. Fernández-Ruiz M, Andrés A, Loinaz C, et al. COVID-19 in solid organ transplant recipients: A single-center case series from Spain. *Am J Transplant.* 2020.
17. Rodriguez-Cubillo B, Moreno de la Higuera MA, Lucena R, et al. Should cyclosporine be useful in renal transplant recipients affected by SARS-CoV-2? *Am J Transplant.* 2020.
18. Travi G, Rossotti R, Merli M, et al. Clinical outcome in solid organ transplant recipients with COVID-19: A single-center experience. *Am J Transplant.* 2020.
19. Ketcham SW, Adie SK, Malliett A, et al. Coronavirus Disease-2019 in Heart Transplant Recipients in Southeastern Michigan: A Case Series. *J Card Fail.* 2020.
20. Nair V, Jandovitz N, Hirsch JS, et al. COVID-19 in kidney transplant recipients. *Am J Transplant.* 2020.

21. Zhu L, Gong N, Liu B, et al. Coronavirus Disease 2019 Pneumonia in Immunosuppressed Renal Transplant Recipients: A Summary of 10 Confirmed Cases in Wuhan, China. *Eur Urol.* 2020;77(6):748-754.
22. Harris PA, Taylor R, Minor BL, et al. The REDCap consortium: Building an international community of software platform partners. *J Biomed Inform.* 2019;95:103208.
23. Harris PA, Taylor R, Thielke R, Payne J, Gonzalez N, Conde JG. Research electronic data capture (REDCap)--a metadata-driven methodology and workflow process for providing translational research informatics support. *J Biomed Inform.* 2009;42(2):377-381.
24. Royston P. Multiple imputation of missing values. *Stata Journal.* 2004;4:227-241.
25. Fishman JA. Infection in Organ Transplantation. *Am J Transplant.* 2017;17(4):856-879.
26. Zhao M, Wang M, Zhang J, et al. Comparison of clinical characteristics and outcomes of patients with coronavirus disease 2019 at different ages. *Aging (Albany NY).* 2020;12.
27. Fabio C, Antonella C, Patrizia RQ, et al. Early predictors of clinical outcomes of COVID-19 outbreak in Milan, Italy. *Clin Immunol.* 2020:108509.
28. Ferguson J, Rosser JI, Quintero O, et al. Characteristics and Outcomes of Coronavirus Disease Patients under Nonsurge Conditions, Northern California, USA, March-April 2020. *Emerg Infect Dis.* 2020;26(8).
29. Buckner FS, McCulloch DJ, Atluri V, et al. Clinical Features and Outcomes of 105 Hospitalized patients with COVID-19 in Seattle, Washington. *Clin Infect Dis.* 2020.
30. Gold JAW, Wong KK, Szablewski CM, et al. Characteristics and Clinical Outcomes of Adult Patients Hospitalized with COVID-19 - Georgia, March 2020. *MMWR Morb Mortal Wkly Rep.* 2020;69(18):545-550.
31. Richardson S, Hirsch JS, Narasimhan M, et al. Presenting Characteristics, Comorbidities, and Outcomes Among 5700 Patients Hospitalized With COVID-19 in the New York City Area. *JAMA.* 2020.

32. Lee LYW, Cazier JB, Starkey T, et al. COVID-19 mortality in patients with cancer on chemotherapy or other anticancer treatments: a prospective cohort study. *Lancet*. 2020.
33. CMS Adult Elective Surgery and Procedures Recommendations: Limit all non-essential planned surgeries and procedures, including dental, until further notice. Baltimore, MD: Centers for Medicare & Medicaid Services, April 7, 2020. (<https://www.cms.gov/files/document/covid-elective-surgery-recommendations.pdf>).
34. American Society of Transplantation. "2019-nCoV (Coronavirus): FAQs for Organ Transplantation." Updated June 18, 2020. Accessed July 12, 2020.

Figure Legends

Figure 1: Unadjusted Kaplan-Meier all-cause mortality within 28-days after COVID-19 diagnosis for selected populations

Figure 2: Medical management of COVID-19 in solid organ transplant recipients in the University of Washington Registry

Pattern frequencies graph representing management strategies used in 482 solid organ transplant recipients with COVID-19, diagnosed between March 1, 2020 and April 15, 2020. Columns show the proportion of patients who received each treatment and are labeled in the format n (%). Treatments used in combination are shown together horizontally.

Figure S1: Consort diagram