Despite increased diagnostic testing capacity for severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), testing in many countries, including the United States, is still inadequate for slowing the coronavirus disease (COVID-19) pandemic. Many persons still do not have access to SARS-CoV-2 testing, and for some that do, an imbalance between supply and demand at large testing centers leads to long delays before results are received. The demand for testing will only increase as many schools, colleges, and workplaces reopen. Ideally, specialized population surveillance–oriented testing would require minimal diversion of resources from clinical diagnostic testing, be affordable and scalable, and enable rapid and reliable virus identification for persons with asymptomatic or subclinical infections. Thus, simplifying the sample collection and testing workflow is critical.

A simple solution is saliva collection. Saliva is a sensitive source for SARS-CoV-2 detection (1–3) and an alternative sample type for antigen and antibody testing (4,5). In addition, saliva collection is noninvasive, can be reliably performed without trained health professionals, and does not rely on a sometimes-limited swab supply. However, almost all saliva-based tests approved by the US Food and Drug Administration require specialized collection tubes containing stabilization or inactivation buffers that are costly and not always available. Moreover, as saliva continues to gain popularity as a potential specimen to aid testing demands, standardized collection methods have not been defined for saliva collection as they have for swab-based specimen collection. When true saliva is not collected (e.g., if it contains sputum), which can happen with COVID-19 inpatients when saliva is difficult to produce, specimens can be difficult to pipette (6). Combined with untested concerns regarding SARS-CoV-2 RNA stability in saliva, using supplements to reduce degradation and improve sample processing has become common. Previous work with saliva samples, however, has indicated that some buffers optimized for host nucleic acid stabilization may actually inhibit viral RNA detection (7) (S.B. Griesemer et al., unpub. data, https://doi.org/10.1101/2020.06.16.20133041), particularly in extraction-free PCRs (D.R.E. Ranoa et al., unpub. data, https://doi.org/10.1101/2020.06.18.159434). Thus, if true saliva (relatively easy to pipette) is being tested, the utility of collecting saliva in expensive tubes containing purported stabilization buffers comes into question. To explore the viability of broadly deploying affordable saliva-based surveillance approaches (8), we characterized SARS-CoV-2 RNA stability and virus infectivity in saliva samples stored in widely

Stability of SARS-CoV-2 RNA in Nonsupplemented Saliva

Isabel M. Ott, Madison S. Strine, Anne E. Watkins, Maikel Boot, Chaney C. Kalinich, Christina A. Harden, Chantal B.F. Vogels, Arnau Casanovas-Massana, Adam J. Moore, M. Catherine Muenker, Maura Nakahata, Maria Tokuyama, Allison Nelson, John Fournier, Santos Bermejo, Melissa Campbell, Rupak Datta, Charles S. Dela Cruz, Shelli F. Farhadian, Albert I. Ko, Akiko Iwasaki, Nathan D. Grubaugh, Craig B. Wilen, Anne L. Wyllie, the Yale IMPACT Research team

Author affiliations: Yale School of Public Health, New Haven, Connecticut, USA (I.M. Ott, A.E. Watkins, C.C. Kalinich, C.A. Harden, C.B.F. Vogels, A. Casanovas-Massana, A.J. Moore, M.C. Muenker, M. Nakahata, A.I. Ko, N.D. Grubaugh, A.L. Wyllie); Yale School of Medicine, New Haven (M.S. Strine, M. Boot, M. Tokuyama, A. Nelson, J. Fournier, S. Bermejo, M. Campbell, R. Datta, C.S. Dela Cruz, S.F. Farhadian, A.I. Ko, A. Iwasaki, C. Wilen); Howard Hughes Medical Institute, New Haven (A. Iwasaki)

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1These first authors contributed equally to this article.
2These senior authors contributed equally to this article.
3Team members team are listed at the end of this article.
available, sterile, nuclease-free laboratory plastic (polypropylene) tubes.

The Study

We used saliva collected from COVID-19 inpatients and at-risk healthcare workers into sterile wide-mouth containers (3) without preservatives (nonsupplemented) to evaluate the temporal stability of SARS-CoV-2 RNA at different holding temperatures (−80°C, 4°C, ≈19°C, 30°C) (Appendix, https://wwwnc.cdc.gov/EID/article/27/4/20-4199-App1.pdf). SARS-CoV-2 RNA from saliva was consistently detected at similar levels regardless of the holding time and temperatures tested. After RNA extraction and quantitative reverse transcription PCR (qRT-PCR) testing for SARS-CoV-2 on the day of saliva collection (3), we aliquoted and stored the remaining 20 sample volumes at −80°C, room temperature (≈19°C), and 30°C. Whether stored at −80°C, room temperature (5 days), or 30°C (3 days), the qRT-PCR cycle threshold (Ct) values for the N1 region of the nucleocapsid protein did not differ significantly from those for samples tested on the day of collection (Figure 1, panel A). After the freeze/thaw cycle or storage at room temperature, we observed Ct decreases of 1.058 (95% CI 2.289 to 0.141) for freeze/thaw and 0.960 (95% CI −2.219 to 0.266) for room temperature; however, the strength of this effect was low. We saw a similar effect after incubation at 30°C, with a Ct increase of 0.973 (95% CI −0.252 to 2.197). Moreover, SARS-CoV-2 RNA remained relatively stable in saliva samples left at room temperature for up to 25 days (Ct 0.027, 95% CI −0.019 to 0.071 Ct) (Figure 1, panel B). Regardless of starting Ct value (viral load), this prolonged stability of SARS-CoV-2 RNA was also observed when samples were stored for longer periods at −80°C (maximum 92 days), 4°C (maximum 21 days), and 30°C (maximum 16 days) (Appendix Figure 1).

Although SARS-CoV-2 RNA from saliva remained stable over time, we observed a decrease in human ribonuclease P at higher temperatures (room temperature, Ct 1.837, 95% CI 0.468 to 3.188 Ct; 30°C, Ct 3.526, 95% CI 1.750 to 5.349 Ct; Appendix Figure 2); the change in concentration was greater than that observed for SARS-CoV-2 RNA (Appendix Figure 3). Thus, although human RNA from saliva degrades without stabilization buffers, SARS-CoV-2 RNA remains protected even at warm temperatures suitable for nuclease activity.

Because saliva has antiviral properties (9,10), we explored the infectiousness of SARS-CoV-2 in saliva samples. We inoculated Vero-E6 cells with 49 saliva samples with higher virus RNA titers (Ct range 13.57–35.32, median 26.01; Appendix Figure 4) because others have shown that SARS-CoV-2 isolation is uncommon from samples with low virus RNA titers (11,12;
By 72 hours after inoculation, C_t values were reduced in 9 (18.7%) of the 49 cultured saliva samples tested by qRT-PCR (−12.90, −11.53, −4.30, −3.68, −3.49, −2.88, −2.81, −2.66, −2.40). Although these findings suggest an increased number of SARS-CoV-2 RNA copies by 72 hours after inoculation (Figure 2), this finding suggests that increased SARS-CoV-2 genome copies identified by qRT-PCR may fall below the limit of detection in plaque assay sensitivity (100 PFU/mL) until a certain reduction in C_t is reached (e.g., C_t reduction ≤12.90) or that components of saliva possibly inhibit active viral particle production and release in vitro. A similar result has been observed when attempting to perform plaque assays of virus from the colon (13), despite studies showing that SARS-CoV-2 infects gut enterocytes (14).

Conclusions
The cost of commercial tubes specialized for saliva collection and SARS-CoV-2 RNA stabilization (>$7/tube) (Table) can be prohibitive for mass testing. Inexpensive saliva-based testing methods are urgently needed to help reach the capacity required to safely reopen schools and workplaces. We demonstrate the stability of SARS-CoV-2 RNA detection in saliva stored for prolonged periods in a variety of settings, which indicates that saliva can be simply collected without the need for additives.

Previous studies have demonstrated the ease with which saliva can be collected into simple, wide-mouth containers (3,15) and that buffers marketed for RNA stabilization may be detrimental to SARS-CoV-2 detection (S.B. Griesemer et al., unpub data, https://doi.org/10.1101/2020.06.16.20133041). Although some of these buffers are also marketed for virus inactivation, SARS-CoV-2 is still considered a Biosafety Level 2 hazard, meaning that with or without buffer, any saliva sample should still be handled with care. Without the need for RNA stabilization and given the limited evidence of virus replication in saliva samples, affordable alternatives to making testing accessible throughout the country are simple, sterile, nuclease-free plastic containers.

SARS-CoV-2 stability at room temperature and at 30°C permits more affordable collection and transport strategies without the need for expensive cooling strategies. Absence of the requirement for cold chain handling also makes saliva testing easier in regions with limited resources. Thus, one key for meeting mass testing demands is collection of saliva in simple, sterile, nuclease-free tubes, negating the high costs associated with specialized collection devices.
Table. Possible saliva collection devices for severe acute respiratory virus coronavirus 2 RNA testing

| Tube type                          | Collection          | Buffer type                                      | Cost per sample, USD | Manufacturer                                |
|-----------------------------------|---------------------|--------------------------------------------------|----------------------|---------------------------------------------|
| Oragene•Dx collection device (OGD-510)* | Funnel              | Ethanol <24%; Tris 1%–5% (host DNA stabilization) | 28.00                | Genotek, https://www.dnagenotek.com         |
| Samplify SD-3000                   | Funnel              | Dry preservative; sodium dodecyl sulfate <1%       | 24.00                | Samplify (URL not available)               |
| Saliva collection kit             | Funnel              | Unknown                                          | 22.47                | IBI Scientific, https://www.ibisci.com      |
| SDNA-1000 small tubes*            | Wide-mouth tube     | Ethanol 10%–25%; Tris 1%–5%; thiocyanic acid:guanidine (1:1) 25%–50%; pH 7.9–8.3 | 17.99                | Spectrum Solutions, https://spectrumsolution.com |
| Saliva RNA Collection and Preservation Device | Wide-mouth tube | Unknown liquid, colorless, odorless | 18                   | Norgen (Biotek), https://norgenbiotek.com    |
| Liquid biopsy/spit devices        | Complicated unit (various) | Unknown                                           | 9–12 each            | Oasis Diagnostics, https://4saliwa.com       |
| OMNiGene•ORAL saliva collection device (OM-505)* | Funnel              | Sodium dodecyl sulfate 1%–5%; glycine,N,N′-trans-1,2-cyclohexanediylbis [N-(carboxymethyl)-,hydrate 1%–5%; lithium chloride 0.5%–1.5% | 9.50                  | Genotek                                     |
| GeneFix Saliva DNA/RNA Collection | Funnel              | Unknown liquid, colorless                         | 9                    | Isohelix, https://isohelix.com              |
| DNA/RNA Shield saliva collection kit* | Wide-mouth tube | Unknown liquid, colorless, pH 5.0–7               | 7.25                 | Zyio Research, https://www.zymoresearch.com |
| Saliva collection system          | Small beaker        | Unknown                                          | Unavailable          | Greiner Bio-One, https://www.gbo.com        |
| Pedia•SAL Infant/Toddler Salivary Collection | Soother + collector | None                                               | Unavailable          | Oasis Diagnostics                           |
| Oral swab                         | Swab                | None                                             | 1.76                 | Salimetrics, https://salimetrics.com        |
| Saliva collection aid + cryovial   | Straw + 2 mL collection vial | None                                               | 1.36/straw, 0.76/vial | Salimetrics                              |
| Urine collection cups             | Wide-mouth cup      | None                                             | 0.47                 | ThermoFisher, https://www.thermoisher.com   |
| Sterile tube, large volume        | Wide-mouth tube     | None                                             | 0.46 (25 mL), 0.38 (5 mL) | Eppendorf, https://www.eppendorf.com       |
| Sterile tube, small volume        | Narrow-mouth tube   | None                                             | 0.16 (2 mL)          | ThermoFisher                               |

*Approved by US Food and Drug Administration Emergency Use Authorization for saliva-based diagnostics.

Yale IMPACT Research Team authors (in alphabetical order): Kelly Anastasio, Michael H. Askenase, Maria Batsu, Sean Bickerton, Kristina Brower, Molly L. Bucklin, Staci Cahill, Yiyun Cao, Edward Courchaine, Giuseppe Deluliiis, Rebecca Earnest, Renata Filler, Bertie Geng, Benjamin Goldman-Israelow, Ryan Handoko, William Khoury-Hanold, Daniel Kim, Lynda Knaggs, Maxine Kuang, Eriko Kudo, Sarah Lapidus, Joseph Lim, Melissa Linehan, Peiven Lu, Alice Lu-Culligan, Amyn A. Malik, Anjelica Martin, Irene Matos, David McDonald, Maksym Minasyan, Nida Naushad, Jessica Nouws, Abeer Obaid, Camila Odio, Ji Eun Oh, Saad Omer, Annsea Park, Hong-Jai Park, Xiaohua Peng, Mary Petrone, Sarah Prophet, Tyler Rice, Kadi-Ann Rose, Lorenzo Sewanan, Lokesh Sharma, Denise Shepard, Mikhail Smolgovsky, Nicole Sonnett, Yvette Strong, Codruta Todeasa, Jordan Valdez, Sofia Velazquez, Arvind Venkataraman, Pavithra Vijayakumar, Elizabeth B. White, Yexin Yang.

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About the Author
Ms. Ott is a research assistant in the Department of Epidemiology of Microbial Diseases at the Yale School.

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of Public Health, New Haven CT. Her work focuses on developing diagnostic tools for and analyzing functional evolution of viral pathogens, with particular focus on SARS-CoV-2 and endemic arboviruses.

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Address for correspondence: Anne L. Wyllie and Nathan D. Grubaugh, Yale School of Public Health, 60 College St, New Haven, CT 06511, USA; email: anne.wyllie@yale.edu and nathan.grubaugh@yale.edu
Stability of SARS-CoV-2 RNA in Nonsupplemented Saliva

Appendix

Methods

RNA extraction and SARS-CoV-2 detection

Saliva samples were self-collected by COVID-19 inpatients and healthcare workers at the Yale-New Haven Hospital (Yale Human Research Protection Program Institutional Review Boards FWA00002571, Protocol ID. 2000027690) (2), into plain wide-mouth containers without the addition of stabilizing buffers. RNA was extracted from saliva samples (1) and tested by RT-qPCR for SARS-CoV-2 RNA (N1) and human RNase P (RP) (3) on day of collection (≤12 hours post sample collection) and at various time points after the storage of the remaining, unsupplemented samples at temperatures of -80°C, -20°C, +4°C, room temperature (measured at an average of ~19ºC), or 30°C.

Cell culture

Vero-E6 cells (ATCC) were cultured in Dulbecco’s Modified Eagle Medium (Gibco) supplemented with 10% heat-inactivated fetal bovine serum (VWR), 1% Penicillin/Streptomycin (Gibco), 100 µg/mL gentamicin (Gibco), and 0.5 µg/mL amphotericin B (Gibco). All cells were incubated at 37°C and 5% CO₂. All cell culture experiments were performed in a biosafety level 3 laboratory at Yale University and approved by the Yale University Biosafety Committee.

Saliva inoculation and virus culture in Vero-E6 cells

Saliva samples were diluted 1:1 in 1X Dulbecco’s PBS (Gibco). Diluted saliva samples were incubated for one hour at 37°C with 2.5x10⁵ Vero-E6 cells in a 24-well plate (Corning). Unbound virus was aspirated and the media were replaced. Infected Vero-E6 cells were frozen at -80°C at 1 and 72 hours post-inoculation. Thawed samples were used for plaque assays and RNA extraction. Prior to RNA extraction (1) and RT-qPCR detection of SARS-CoV-2 RNA (3) the Vero-E6 cells from 1 and 72 hours post-inoculation were thawed at room temperature and further
lysed by diluting 1:3 in MagMax Binding Solution (ThermoFisher). RNA was extracted from the two timepoints and tested in RT-qPCR for SARS-CoV-2 N1. We interpreted a Ct reduction >2 as a difference which could potentially be explained by viral replication during the two timepoints.

**Plaque assay**

Vero-E6 cells were seeded at 4x10⁵ cells/well in 12-well plates (Corning). The following day, media were removed and replaced with 100 μl of 10-fold serial dilutions of thawed 1 hour or 72 hour post-inoculation saliva samples. Plates were incubated at 37°C for 1 hour with gentle rocking every 15 mins. Unbound inocula was aspirated from each well and overlay media (DMEM, 2% FBS, 0.6% Avicel RC-581 (DuPont)) were added to each well. At 48 hours post-infection, plates were fixed with 5-10% formaldehyde for 30 min then stained with crystal violet solution (0.5% crystal violet in 20% ethanol) for 30 mins. Crystal violet solution was then aspirated and plates were washed in tap water to visualize plaques.

**Statistical analyses**

We fit a linear regression to the experimental stability data to model the change in Ct values of positive samples following stability conditions using the equation below. Let dct be the change in Ct value from fresh testing following each storage condition and let condition be the categorical storage condition (e.g. freeze/thaw, room temperature, 30°C, etc).

\[ dct \sim \text{condition} \]

Robust confidence intervals were simulated from this model using the mvrnorm, in the R package “MASS”, and quantile functions. This regression was also used to model the effect of prolonged storage in stability conditions on RP.

For extended timepoint analyses of N1 we used a linear mixed effects model to predict the change in Ct values of positive samples under each stability condition for greater durations of time using the equation below. Let timepoint be the number of days under stability conditions and let sample be the patient number.

\[ dct \sim \text{timepoint} + (1|\text{sample}) \]

Confidence intervals were computed for this model using confint.merMod, in the R package “lme4”.

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Further statistical analyses were conducted in GraphPad Prism 8.0.0 as described in the text and figure legends.

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Appendix Figure 1. Stability of SARS-CoV-2 RNA (N1) detection in saliva. SARS-CoV-2 RNA detection in saliva on day of sample collection (0) or after prolonged storage at -80°C, 4°C or 30°C. Ct values from the same original sample are connected by a dotted line. The -80°C and 4°C conditions were found to have a weakly beneficial effect on signal detection by the mixed effects model, while the 30°C condition resulted in a slight increase in Ct. The -80°C storage alone did not cross zero suggesting a mildly stronger effect than the other conditions (95% CI: -0.038, -0.010). The black dashed line represents Ct 38 which we applied as the cut-off to determine sample positivity. Samples that remained not detected (ND) after 45 cycles are depicted as Ct 42.
Appendix Figure 2. Detection of human RNase P (RP) declines over time when stored in saliva in warmer conditions. Detection of human RP in saliva on day of collection (0) or after prolonged storage at -80°C, 4°C, room temperature (~19°C) or 30°C. Ct values from the same original sample are connected by a dotted line. Prolonged storage at -80°C and 4°C had minimal effect on RP detection with Ct changes of 0.832 (95% CI: -0.402, 2.038) and -0.315 (95% CI: -2.336, 1.687), respectively. However, storage at room temperature (Ct +1.837, 95% CI: 0.468, 3.188) and 30°C (Ct +3.526, 95% CI: 1.750, 5.349) was detrimental to RP, exhibiting a more substantial decrease in signal at these warmer conditions. The black dashed line represents Ct 38 which we applied as the cut-off to determine sample positivity. Samples that remained not detected (ND) after 45 cycles are below the y-axis limit.
Appendix Figure 3. Detection of SARS-CoV-2 RNA (N1) in saliva remained more stable over time than human RNase P (RP). Delta Ct was calculated as the difference in Ct value from the day of saliva collection and after storage at -80°C, 4°C, room temperature (~19°C) or 30°C. Delta Ct values from the same sample are joined by a solid line. While the change in detection of SARS-CoV-2 N1 and RP was similar in saliva samples stored at 4°C (Wilcoxon signed rank test, \( p = 0.129 \)), a greater difference was observed between the change in N1 and RP for samples stored at -80°C (\( p = 0.001 \)), room temperature (\( p = 0.001 \)) and 30°C (\( p < 0.0001 \)).
Appendix Figure 4. Saliva samples of relatively high viral load were cultured to evaluate the infectiousness of SARS-CoV-2 in saliva. Saliva samples cultured on Vero-E6 to test for infectious virus were of higher SARS-CoV-2 RNA (N1) load as compared to the overall saliva samples collected by Yale IMPACT (2) which tested positive for SARS-CoV-2 (Mann-Whitney, $p < 0.0001$). The orange diamond depicts the only sample that produced plaque forming units following 72 hours of culture (PFU; titer increase of 3.79e4 PFU/mL)