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 We have a number of manuscripts and preprints that describe using these assays. Please contact [aboehm@stanford.edu](mailto:aboehm@stanford.edu) or check out the website: [www.stanford.edu/~aboehm/research.htm](http://www.stanford.edu/~aboehm/research.htm)

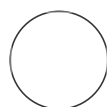
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Quantification of various SARS-CoV-2 variant mutations (characteristic of Alpha, Beta, Gamma, Delta, Omicron and Omicron sublineages) in settled solids using digital RT-PCR V.11

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## ABSTRACT

This process instruction describes the steps for quantitative analysis of nucleic acid from SARS-CoV-2 with a triplex Reverse Transcriptase droplet digital Polymerase Chain Reaction (RT-ddPCR) assay targeting the N Gene, S Gene and various mutation assays in extracted and purified RNA samples from solid wastewater samples for population level SARS-CoV-2 community surveillance. RT-ddPCR is a modified version of conventional RT-PCR workflows which involves separating the reaction mixture into many partitions (~20,000) before thermal cycling which allows for direct absolute quantification of the target RNA molecules.

**Protocol status:** Working  
We use this protocol and it's working

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**PROTOCOL integer ID:**  
76242

**Keywords:** SARS-CoV-2, wastewater, alpha, beta, gamma, variant, mutation, COVID-19

Future protocols will be published that are complementary to this one and describe assays targeting additional SARS-CoV-2 mutations.

This protocol uses RNA extracted using this protocol: [High Throughput RNA Extraction and PCR Inhibitor Removal of Settled Solids for Wastewater Surveillance of SARS-CoV-2 RNA](#). That RNA is generated from samples subjected to pre-analytical steps outlined in: [High Throughput pre-analytical processing of wastewater settled solids for SARS-CoV-2 RNA analyses](#). It is recommended that these assays be run along assays for PMMoV and BCoV as controls as described in the companion protocol [High Throughput SARS-COV-2, PMMOV, and BCoV quantification in settled solids using digital RT-PCR](#)

The readout of this assay is a concentration of each target in the extracted RNA samples (copies/μL).

### Scope

This process instruction applies to quantitative analysis of nucleic acid from SARS-CoV-2 RNA from solid wastewater samples with ddPCR using a Bio-Rad AutoDG Droplet Digital PCR system consisting of the AutoDG Automated Droplet Generator and the QX200 droplet reader.

### Publications

The following publications describe use of these assays:

M. K. Wolfe, B. Hughes, D. Duong, V. Chan-Herur, K. R. Wigginton, B. White, A. B. Boehm. 2022. Detection of SARS-CoV-2 variant Mu, Beta, Gamma, Lambda, Delta, Alpha, and Omicron in wastewater settled solids using mutation-specific assays is associated with regional detection of variants in clinical samples. *Applied and Environmental Microbiology*. 88(8), e00045-22.[Link](#).

A. B. Boehm, B. Hughes, M. K. Wolfe, B. J. White, D. Duong, V. Chan-Herur. Regional replacement of SARS-CoV-2 variant Omicron BA.1 with BA.2 as observed through wastewater surveillance. Accepted to *Environmental Science & Technology Letters*.[Link to preprint](#).

Kirby AE, Welsh RM, Marsh ZA, Yu AT, Vugia DJ, Boehm AB, Wolfe MK, White BJ, Matzinger SR, Wheeler A, Bankers L, Andresen K, Salatas C, NYDEP, Gregory DA, Johnson MC, Trujillo M, Kannoly S, Smyth DS, Dennehy JJ, Sapoval N, Ensor K, Treangen T, Stadler LB, Hopkins L. 2022. Notes from the Field: Early Evidence of the SARS-CoV-2 B.1.1.529 (Omicron) Variant in Community Wastewater - United States, November - December 2021. *MMWR Morb Mortal Wkly Rep* 2022;71:103- 105. DOI:<http://dx.doi.org/10.15585/mmwr.mm7103a5>.

A. Yu, B. Hughes, M. Wolfe, T. Leon, D. Duong, A. Rabe, L. Kennedy, S. Ravuri, B. White, K. Wigginton, A. Boehm, D. Vugia. 2022. Estimating relative abundance of two SARS-CoV-2 variants through wastewater surveillance at two large metropolitan sites. *Emerging Infectious Disease*, 28(5), 940-947. [Link](#).

## MATERIALS

### Equipment

- Bio-Rad QX200 AutoDG
- Bio-Rad QX200 Droplet Reader
- Bio-Rad PX1 PCR Plate Sealer (Bio-Rad, Catalog #:1814000)
- Agilent Bravo
- Eppendorf Master Cycler ProThermal Cycler
- Bio-Rad C1000 Touch Thermal Cycler
- Rainin Single-Channel Pipettes L1000XLS+, L200XLS+, L20XLS+, L10XLS+, , L2XLS+
- Rainin Multi-Channel Pipettes L12-1000XLS+, L12-200XLS+, L12-20XLS+, L12-10XLS+, L8-1000XLS+, L8-200XLS+, L8-20XLS+, L8-10XLS+
- Axygen Plate Centrifuge
- Benchtop vortex
- 96-well plate cold block for AutoDG droplet generator
- 96-well plate cold block for ddPCR plates
- Zebra GX430t label printer

### Reagents

- ddPCR™ One-Step RT supermix for Probes
- Reverse Transcriptase
- 300mM DTT
- Automated Droplet Generation Oil for Probes
- Ambion Nuclease Free Water, 50mL
- ddPCR Droplet Reader Oil

### Consumables

- Bio-Rad ddPCR™ 96-Well Plates
- Eppendorf twin.tec PCR Plate
- DG32™ Automated Droplet Generator Cartridges
- PCR PX1 Plate Sealer, foil, pierceable
- Pipet Tips for the AutoDG™
- Rainin low retention, pre-sterilized, filter tips 1000 µL, 200 µL, 20 µL
- Axygen Automation Tips, 20 µl, filtered, sterile tips (Axygen 20 µL tips)

- Reagent Reservoirs
- Automation Reservoirs
- Eppendorf Tubes, 1.5mL, 2mL and 5mL.
- 2.5" x 0.5" Cryogenic Labels for the Zebra GX430t label printer

### Samples and Test Materials

- Purified RNA from wastewater samples as described in [High Throughput RNA Extraction and PCR Inhibitor Removal of Settled Solids for Wastewater Surveillance of SARS-CoV-2 RNA](#)
- SARS-CoV-2 gRNA positive control (ATCC® VR-1986D™) diluted and aliquoted at a concentration of 50 copies per  $\mu\text{L}$ .
- Synthetic gene block containing the mutations purchased from IDT diluted and aliquoted at a concentration of 50 copies per  $\mu\text{L}$ .
- Heat inactivated SARS-CoV-2 B.1.1.7 (ATCC VR-3326HK™) diluted and aliquoted at a concentration of 50 copies per  $\mu\text{L}$ . Note: no RNA extraction is done.
- Other possible positive controls include cultivated viral RNA or TWIST synthetic genomes

### Primer and Probe Sequences

See companion protocol for N and S gene primers and probes: [High Throughput SARS-COV-2, PMMOV, and BCoV quantification in settled solids using digital RT-PCR](#).

Additional protocols will be published or this protocol may be update to describe primer and probe sequences targeting other SARS-CoV-2 mutations.



A	B	C
Target	Primer/Probe	Sequence
HV69-70 del	Forward	ACTCAGGACTTGTTCTTACCT
present in Alpha, BA.1, BA.4, and BA.5	Reverse	TGGTAGGACAGGGTTATCAAAC
	Probe	ATGCTATCTCTGGGACCAAT (5' FAM or HEX/ZEN/3' IBFQ)
E484K/N501Y	Forward	CTGAAATCTATCAGGCCGGT
present in beta and gamma	Reverse	GTTGGTAACCAACACCATAAG
	Probe	CACACCTTGTAATGGTGTAAAGGTT (5' FAM or HEX/ZEN/3' IBFQ)
del156-157/R158G	Forward	ATTCGAAGACCCAGTCCCTA


A	B	C
present in Delta	Reverse	AGGTCCATAAGAAAAGGCTGA
	Probe	TGGATGGAAAGTGGAGTTTATTCTAG (5' FAM or HEX/ZEN/3' IBFQ)
Del143-145	Forward	ATTCGAAGACCCAGTCCCTA
present in Omicron BA.1	Reverse	ACTCTGAACTCACTTTCCATCC
	Probe	TTGTAATGATCCATTTTTGGACCACAA (5' FAM or HEX/ZEN/3' IBFQ)
LPPA24S	Forward	GCCACTAGTCTCTAGTCAGTGTG
present in Omicron BA.2, BA.4, and BA.5	Reverse	TGTCAGGGTAATAAACACCACGT
	Probe	CAGAACTCAATCATACACTAATTCTTTTAC (5' FAM or HEX/ZEN/3' IBFQ)
S:477-505	Forward	CTATCAGGCCGGTAACAAAC
present in Omicron BA.1, BA.2, BA.4, and BA.5	Reverse	ACTACTCTGTATGGTTGGTGAC
	Probe	CCTTTACGATCATATRGTTTCCGACCC (5' FAM/ZEN/3' IBFQ)
ORF1a: del141-143	Forward	TAATAAAGGAGCTGGTGGCC
present in Omicron BA.4	Reverse	ATGAGTTCACGGGTAACACC
	Probe	CGGCGCCGATCTAGACTTAG (5' FAM/ZEN/3' IBFQ)
S:K147E & S:W152R	Forward	CGAAGACCCAGTCCCTACTT
present in Omicron BA.2.75 and BA.2.75.2	Reverse	TCCATAAGAAAAGGCTGAGAGA
	Probe	CCACGAAAACAACAAAAGTCGGATG (5' FAM/ZEN/3' IBFQ)
Y445P, G446S, E484A, F486S/P and F490S	Forward	GGCTGCGTTATAGCTTGGAA

	A	B	C
	Present in XBB*	Reverse	GAGAGTAACAATTAGRACCTGCAAC
		Probe	CTTGATTCTAAGCCTAGTGGTAATTATAAT (5' FAM/ZEN/3' IBFQ)

Primer and probes for the mutation assays. They are to be multiplexed with the assays for N and S as described in our companion protocol.

## Preparation



- 1 Retrieve all kit components from the One-Step RT-ddPCR advanced kit for probes from the  -20 °C freezer and thaw the components  On ice .

 One-Step RT-ddPCR Advanced Kit for Probes **BioRad Sciences Catalog #186-4021**


### Note

This protocol describes a triplex assay for the N, S, and a mutation gene. Protocols targeting the HV69-70 deletion, E484K/N501 mutation, del156-157/R158G, del143-145, LPPA24S, S:477-505, ORF1a Del 141-143, and S:K147E & S:W152R are in this document, but it is possible to swap out one or two of the assays for others that also target low copy number targets using the same procedure. However, we do not recommend multiplexing with a high copy number target like PMMoV because a high copy number target assay would need to use diluted RNA as template.

Note that all primer and probe sequences are provided in the "Materials" link.

- 2 Retrieve ddPCR positive control aliquots (50 copies per uL gRNA) from the  -80 °C freezer and thaw  On ice

- 3 **For re-running frozen plates only:**

Thaw the RNA storage plate  On ice . Before analysis of thawed frozen samples, ensure that the plate is adequately sealed and briefly vortex and centrifuge the plate to ensure the samples are well mixed.


- 4 Keep extracted RNA samples  On ice or in a cold block from the freezer at all times.

## ddPCR master mix preparation

45m

### 5 Prepare Master Mix

- 5.1 Prepare a working stock of fresh nuclease free water by pouring from a 50 mL Ambion Nuclease Free water into a 5mL eppendorf tube.

- 5.2 Store Master Mix components  On ice as much as possible during the preparation process.

- 5.3 Briefly vortex One-Step RT supermix for Probes (Yellow Tube), Reverse Transcriptase (Orange Tube), and DTT (Grey Tube) to mix contents then briefly spin with the benchtop centrifuge.

 One-Step RT-ddPCR Advanced Kit for Probes **BioRad Sciences Catalog #186-4021**

- 5.4 In a 2mL eppendorf tube, prepare the master mix according to the table for SARS-CoV-2 quantification with HV69-70, E484K/N501Y, or del156-157/R158G. Store prepared master mix on ice.

### Note

Additional protocols will be published for other mutations associated with SARS-CoV-2 variants.

### Primer/Probes Mixes

A	B	C
	20x Concentration	Final Concentration/Rxn
Primers (each)	18 $\mu$ M	900 nM
N Probe (FAM)	5 $\mu$ M	250 nM
S Probe (HEX)	5 $\mu$ M	250 nM
XXX Probe (HEX)	2.5 $\mu$ M	125 nM
XXX Probe (FAM)	2.5 $\mu$ M	125 nM

The 20x SARS-CoV-2 and XXX Primer/Probe Mix contains primers and probes in the following concentrations (suspended in molecular grade water). XXX is the mutation of interest.

### Master Mix

A	B	C
Reagents	Volume per Well	Volume Per Plate
ddPCR™ One-Step RT supermix for Probes (Yellow Tube)	5.5 $\mu$ L	580.8 $\mu$ L
20x SARS-CoV-2 Primer/Probe Mix	3.3 $\mu$ L	348.48 $\mu$ L
Reverse Transcriptase (Orange Tube)	2.2 $\mu$ L	232.32 $\mu$ L
300mM DTT (Gray Tube)	1.1 $\mu$ L	116.16 $\mu$ L
Nuclease Free Water	4.4 $\mu$ L	464.64 $\mu$ L
Total Volume	16.5 $\mu$ L	1742.4 $\mu$ L

SARS-CoV-2 ddPCR Master Mix. Volume per plate assumes 96 well plate (with 10% excess).








## Transfer Master Mix and Samples to ddPCR plate

- 6 For each assay, remove a cold block from the freezer and place a new Bio-Rad ddPCR 96-well Plate in it.

### Note

Note that these steps may be completed with a liquid handling robot. We use the BRAVO system.

- 7 Using a new reagent reservoir, manually pipette  16.5 µL of the appropriate Master Mix to each well of each ddPCR Plate.
- 8 Transfer samples to the following wells on the plate either manually or using a liquid handling robot such as the Agilent Bravo system:
- Transfer  5.5 µL of samples from columns 1-10 of the RNA plate into columns 1-10 of the ddPCR plate.
  - Transfer  5.5 µL of the extraction controls from column 12 of the RNA plate into column 11 of the ddPCR plate.
  - Transfer  5.5 µL of NTC (water) into A-G of column 12.
  - Add  5.5 µL of ddPCR positive control to well H12 of the ddPCR plate (add manually even if using a liquid handler)

### Note

Use SARS-CoV-2 genomic RNA (ATCC® VR-1986D™) mixed 1:1 with appropriate mutation standard as ddPCR positive control (see materials section of the protocol). The extraction positive controls are generated during RNA extraction per this companion protocol: <https://www.protocols.io/view/high-throughput-rna-extraction-and-pcr-inhibitor-r-btyrnpv6>. In that protocol, the extraction positive control consists of SARS-CoV-2 genomic RNA that does not contain the mutations HV69-70 and E484K/N501Y or other mutation targets.

The plate layout should be:

	1	2	3	4	5	6	7	8	9	10	11	12
A	Sample 1										Extraction Negative control	NTC
B	Sample 2											
C	Sample 3											
D	Sample 4											
E	Sample 5											
F	Sample 6											
G	Sample 7											
H	Sample 8										Extraction Positive control	ddPCR Positive control

#### Note


Note: The set up of this plate is slightly different from the set up of the 96 well extraction plate used in our companion protocol. Column 11 of this plate uses column 12 of the extraction plate. The lower right hand corner was purposely chosen for the placement of the positive controls.

- 9 Bring the BioRad ddPCR plate with Master Mix and samples to the Bio-Rad PX1 PCR Plate Sealer and place it in the metal carrier inside the plate sealer.

#### Note

Do not store the metal carrier inside the plate sealer, as it will become warm and warm the samples during sealing.

- 10 Align a PCR Plate Heat Seal Foil on top of the ddPCR plate with the red line facing up.
- 11 Seal the plate by pressing the green “seal” button.
- 12 Briefly vortex the plate using a bench top plate vortexer.

- 13 Briefly spin down the plate in the bench top Axygen Plate Centrifuge.
- 14 Store the ddPCR plate on a white cold block or  On ice until droplet generation.

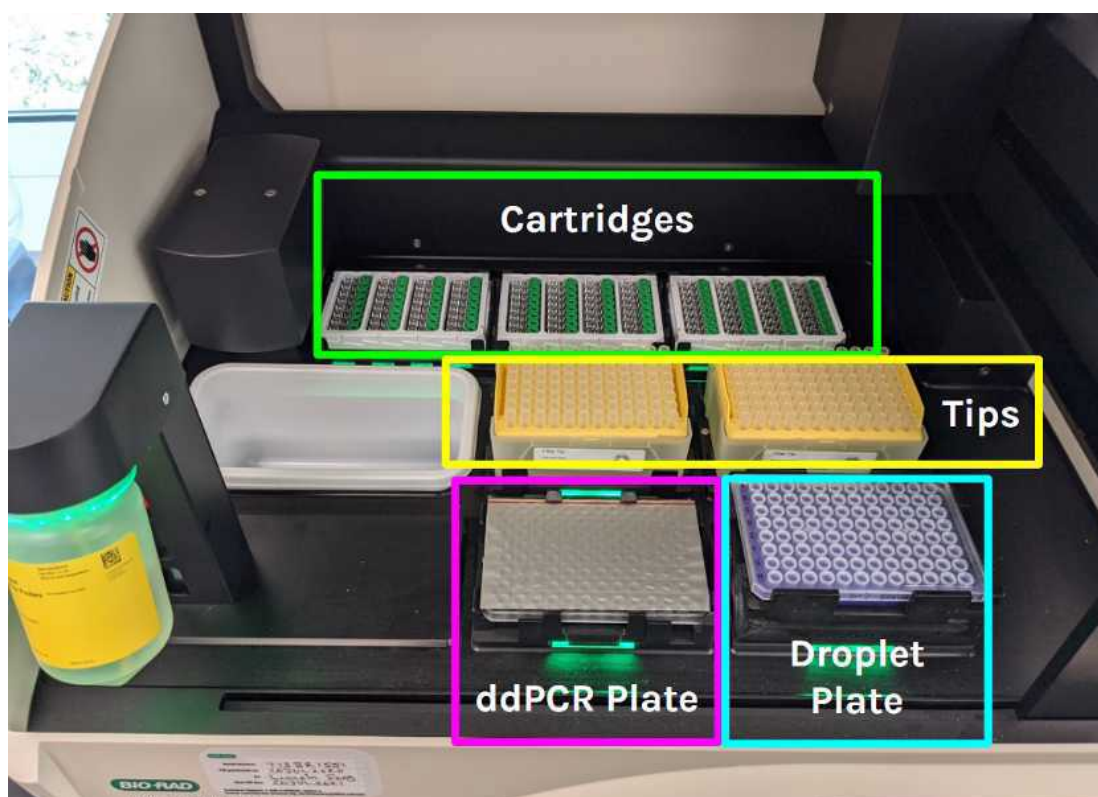
## ddPCR droplet generation

45m

- 15 Generate Droplets:
  - 15.1 On the AutoDG droplet generator: select “configure plate” and then press the blue arrow in the upper left corner to highlight all columns.
  - 15.2 Load 3 DG32 cartridge plates and 2 tip boxes with the lid removed onto the AutoDG deck. The icons on the AutoDG display will change from yellow to green if the plates and tips are oriented correctly.
  - 15.3 Place the sealed, vortexed, and centrifuged ddPCR plate in the Sample Plate position on the AutoDG deck.
  - 15.4 Remove the AutoDG cooling block from the freezer and place it in the Droplet Plate slot on the AutoDG deck.
  - 15.5 For the Droplet Plate: label a new Bio-Rad ddPCR™ 96-Well Plate and place it in the Auto DG cooling block.

- 15.6** Click “Generate Droplets” to begin droplet generation. Droplet generation will take approximately 🕒 00:45:00 .

45m



- 15.7** When droplet generation is done, open the lid and remove the droplet plate from the Auto DG cold block and place it in the metal carrier inside the plate sealer.

**Note**

The droplets are highly unstable at this stage. The droplets should not be left on the generator longer than they need to be. Once thermocycled the droplets are more stable.

- 15.8** Align a PCR Plate Heat Seal Foil on top of the droplet plate with the red line facing up.

- 15.9 Seal the plate by pressing the green “seal” button.

Note

**NOTE:** Do NOT vortex plate at this point!

## Thermocycling

45m

- 16 Place the plate in the thermocycler. Verify and run the thermocycler program according to the table for SARS-CoV-2 ddPCR.

Note

The annealing temperature for the multiplex assay for N, S, and HV69-70 is 59°C and N/S/ all other mutations is higher (61°C). A higher annealing temperature is necessary to ensure high specificity for the other mutation assays, and we found that the N and S assays performed with the same amplitude/efficiency of reaction at 61°C as at 59°C.


For additional mutation assays, see those protocols for thermocycling conditions and take note of differences in recommended annealing temperature.

A	B	C	D
Steps	Cycle #s	Temp (°C)	Time
1	1	50	60 min
2	1	95	5 min
3	40	95	30 secs
	40	59	1 min
4	1	98	10 min
5	-	4	hold

Cycling conditions for the N/S/HV69-70 multiplexed assay

A	B	C	D
Steps	Cycle #s	Temp (°C)	Time
1	1	50	60 min
2	1	95	5 min
3	40	95	30 secs
	40	61	1 min
4	1	98	10 min
5	-	4	hold

Cycling conditions for the N/S/XXX multiplexed assay where XXX are all other mutations.

- 16.1** After the PCR program is done, store the ddPCR plate at  4 °C (in the thermal cycler, on ice or in the fridge) until droplet reading.

## Read Droplets

- 17** Before running the plate on the QX200 droplet reader, open the drawer on the left side of the instrument and check that there is adequate droplet reader oil and that the waste bottle is not overly full.
- 18** Load template from previous plate of the same assay - ensure that all parameters (supermix, dye, absorbance etc.) are correct for the assay used and that sample names are assigned to the appropriate wells. Save as with a new plate name.

### Note

Double check that the correct supermix label is used for the read and that the channels are labeled appropriately. These parameters can NOT be changed after you run the plate.

- 19** Name the file with a name clearly describing which plate you are reading.

- 20 Remove the plate from the thermal cycler and secure it in the droplet reader by placing it in the stage, placing the metal brace on top of it and pressing down the black plastic tabs on either side of the brace.
- 21 Click "Run" in Quantasoft to commence droplet reading.  
Select "Ok" when the next dialog box comes up. Do not change the settings from "Columns" and "FAM/HEX".

## Post-Processing Analysis

- 22 SARS-CoV-2 triplex assay analysis
  - 22.1 Open QuantaSoft™ Analysis Pro Software
  - 22.2 Open the .qlp file associated with the run
  - 22.3 1.1.1. On the Plate Editor tab, select all the wells then in the dropdown menu for Assay Information select Probe Mix Triplex and complete as follows and click "Apply":

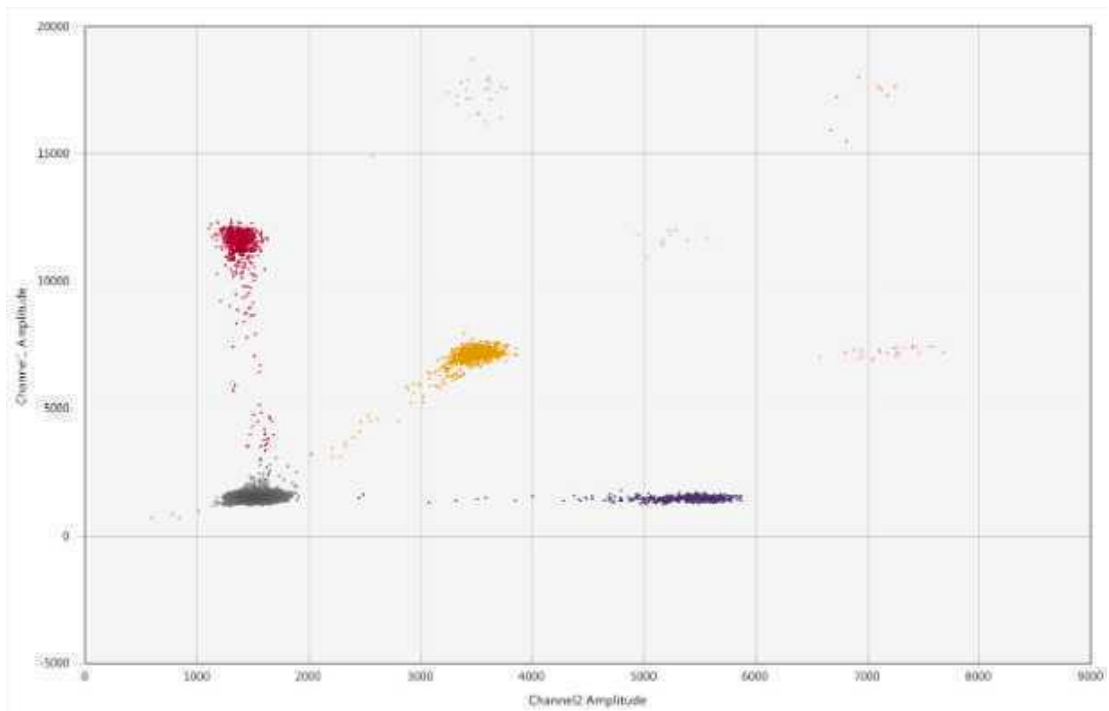
Assay Information

Probe Mix Triplex ▼ Apply

Target Name	Target Type	Signal Ch1	Signal Ch2
N Gene	Unkn ▼	FAM ▼	None ▼
S Gene	Unkn ▼	None ▼	HEX ▼
Mutation gene target	Unkn ▼	FAM ▼	HEX ▼

- 22.4** At this point, if sample names were not added at the start of the run, fill in the sample name by selecting the wells, typing in sample ID and click “Apply”.
- 22.5** If wells need to be deselected: Go to the Plate Editor tab, select wells to exclude and click “Clear Selected Well”.
- 22.6** On the 2D Amplitude tab, make sure that all wells are highlighted and select the Threshold Cluster Mode Graph Tool and draw 2D thresholds around each cluster as follows





- 22.7** Go through every well to ensure that:
- The droplets are designated properly per well
  - There are >10,000 droplets per well

- 22.8** If any well does not have the appropriate droplets, go to the Plate Editor tab, select the affected well and click “Clear Selected Well”.

- 22.9** On the 2D Amplitude tab, select Merged Wells on the left side of the page

- 22.10** Click on the Table Menu Button on the right side of the Well Data table and select Export to CSV to export data.

- 22.11** Save the QuantaSoft Analysis

## Dimensional Analysis and Quality Control

**23** For dimensional analysis to express the results of each assay in terms of gene copies/dry weight solids:

**23.1** Begin with the concentration provided by the QuantaSoft software and reported in the CSV, as expressed in gc/uL of reaction.

### Note

This concentration is expressed in terms of the total volume of the merged wells, rather than the volume of the template added. Determination of gc/g relies on the ratio of of template in the reaction and mass in the volume eluted from extraction, so when beginning with this value expressed in terms of gc/uL the number of wells merged is not considered in the dimensional analysis.

**23.2** To determine the concentration in cp/g dry weight:

$$\frac{X \text{ copies}}{\mu\text{l rxn}} * \frac{B \mu\text{l rxn}}{A \mu\text{l template}} * \frac{C \mu\text{l total eluent from extraction kit}}{Z \text{ g wet mass solids added to extraction kit}} * \frac{1}{\% \text{ solids}}$$

## Note

When using the assays described in the three protocols that make up this process as written:

- B = 20  $\mu$ L total reaction volume
- A = 5  $\mu$ L volume template in reaction
- C = 60  $\mu$ L elution volume from each well in extraction kit
- Z = 0.0225 g wet weight of solids added to each extraction well (300  $\mu$ L of a suspension of 75 mg wet weight solids / ml of solution)
- Percent solids varies for each sample on each day (typical range 0.05 - 0.3, i.e. 5-30%)

Please note that there are many different ways to conceptualize the dimensional analysis. Please be sure to double check your own calculations to make sure they match with the measurement units from your instrument. For example, our instrument reports results as copies per the entire volume of the rxn, but some instruments may report a different concentration.

Links to two companion protocols to this protocol can be found in the description of this protocol.