Final Report for:

MOO Print Ltd.

London, United Kingdom

Evaluation of Community Face Coverings

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A. Executive Summary

The Golisano Institute for Sustainability (GIS) at Rochester Institute of Technology (RIT) conducted a project entitled, “Evaluation of Community Face Covering” for MOO Print Ltd. (MOO) to perform a side-by-side evaluation of their cotton paper based community face coverings versus disposable Commercial-Off-The-Shelf (COTS) non-medical face coverings. The objective of the evaluation was to estimate the relative amount of droplets expelled through or passed the face coverings. The model of the MOO face covering evaluated was specified by MOO as “Paper Face Mask by MOO production version approved December 1, 2020” that had printing on the outside.

For this project, GIS setup a visualization system to evaluate simulated cough droplets that scatter light as they propagate through a laser beam after being expelled from the MOO and COTS face coverings compared no face covering. The setup used a line laser to create a light plane next to a mannequin head so that a camera could detect the droplets during a simulated cough. A software algorithm was developed to quantify the number of activated camera pixels and the change in pixel brightness levels for use as a proxy in estimating the number of droplets expelled beyond each face covering. Two primary tests were conducted: 1) with the laser planes within 32mm of the mannequin head for four consecutive views to enable imaging of droplets moving in varying directions, and 2) with the laser plane 0.6m from the front of the face to evaluate droplets moving in the forward direction. This second test was performed by moving the camera for multiple coughs to effectively capture a larger field of view by spatially stitching together videos. The results of the work include measurements summarized below and the data provided in Table 1 and Table 2.

Based on RIT’s use of overall relative pixel brightness as a proxy for the measurement of droplets in still air, the results of the first set of tests (laser planes within 32mm of the mannequin head for a Front, Side, Top and Bottom view) concluded:

- Both MOO and COTS face covering evaluations indicated that wearing a face covering limited the droplets expelled in the Front view compared to not wearing a face covering.
- MOO face coverings released fewer droplets in the Front and Side views compared to the COTS face covering.
- MOO face coverings released more droplets in the Bottom and Top views compared to the COTS face covering.

- There was a statistical difference in the total overall relative pixel brightness of both the MOO and the COTS face coverings compared to no face covering under these test conditions.
- There was no statistical difference, at a confidence interval (CI) of 95%, in the total overall relative pixel brightness of the MOO face coverings compared to the COTS face covering under these test conditions.

Table 1: Summary of Test Results with Laser Plane within 32mm of the Head

	Overall Relative Pixel Brightness (%) [Mean]				
	Front	**Side(x2)***	**Bottom**	**Top**	**Approximate Total****
No Face Covering	10.7	0.06	0.23	0.01	11.0
MOO Face Coverings	0.03	0.50	1.53	3.80	5.9
COTS Face Coverings	0.14	3.58	0.65	1.67	6.0
Statistically Significant Difference at 95% CI between MOO and no face covering?	Yes	Yes	No	Yes	Yes
Statistically Significant Difference at 95% CI between MOO and COTS?	Yes	Yes	No	Yes	No

*Assumed symmetric release of droplets about the mannequin head for this experiment.

**Totals are based on a summation of all views; however, the camera working distances and lighting may differ between setups; therefore, the Total is considered only directionally accurate. Testing behind the head was not performed, which may increase the total for the MOO and COTS face coverings. All tests were conducted with droplet sizes of approximately 10µm and without measurable air flow.

Based on RIT's use of overall relative pixel brightness as a proxy for measurement of droplets in still air, for a laser plane at a distance of 0.6m in front of the mannequin head (facing the cough) the data showed:

- Both MOO and COTS face coverings limited the droplets expelled in the forward direction compared to no face covering.
- MOO and COTS face coverings exhibited similar measurements for droplets traveling a distance of 0.6m in the Front view.

Table 2: Summary of Test Results with Laser Plane 0.6 meters from the Head – Multiple Images Stitched together to effectively capture a 0.9 x 0.9 meter² Area

	Overall Relative Pixel Brightness (%), Front View* [Mean]
No Face Covering	2.2
MOO Face Covering	0.14
COTS Face Covering	0.18

*without measurable air flow that may affect droplet movement

The results presented in this report are subject to limitations of the evaluation method and specific to the test setup, including: a room size of 4.2 meters by 4.5 meters by 5.5 meters, relative humidity level of 14 percent, room temperature of 20.6°C, use of water for the droplet media, size of the droplets, mechanism to create droplets, room temperature water, floor temperature of 20.6°C, average cough rate of 1.5 liters per second with a volume of 3.6 liters, still ambient air, use of a hard plastic mannequin head, and camera system. These study findings should not be considered representative of use in real world settings and should only be used as a relative indicator of effectiveness. The findings of this evaluation should not be generalized to other face coverings[1].

The evaluations performed for this project were best-effort to provide MOO with information on expulsion of droplets passed face coverings. RIT's evaluation should not be confused with certification for medical use. Based on the results associated with the mannequin head used, the MOO face covering fit around the chin and nose are areas where product enhancements may more effectively prevent release of droplets in the Bottom and Top views. Different sized face coverings to accommodate larger and smaller head sizes may provide additional capture or obstruction of expelled droplets.

B. Background

MOO is a design, technology, and manufacturing company founded in London with a U.S. base of operations in Lincoln, RI. MOO has seen the news coverage of the ecological impact of disposable plastic face coverings and in response, has worked over the past few months to develop a single-use face covering using cotton paper created out of T-shirt offcuts (a waste product of the garment industry).

[1] https://www.cdc.gov/mmwr/volumes/70/wr/mm7007e1.htm#contribAff

MOO has been following the research out of Universities on the effectiveness of various face coverings in controlling the distribution of respiratory droplets as a means of slowing the spread of COVID-19, and believe they can replace the widely distributed disposable, plastic covering with a paper substitute. MOO is seeking to perform a side-by-side comparison of the MOO paper face covering with a non-medical disposable plastic face covering using a technique similar to the aforementioned university studies for the visualization of emulated coughs that travel toward others. MOO will use this visualization to refine the design based on the insights gleaned from this evaluation. MOO knows that there are limitations to the potential effectiveness of a paper face covering; however, they believe their product can replace the widely distributed disposable, plastic face coverings with a paper substitute.

There are no regulatory test standards known by the research team for thorough testing of community face coverings in the U.S.; however, there are reports that development of a standard is underway by American Society for Testing and Materials (ASTM) for non-medical uses[2]. Upon issuance of such standards, RIT recommends a subsequent study to test the MOO face covering product to the standards.

C. Project Objective

The objective of this project was to perform a side-by-side comparison of relative amount of droplets expelled through a laser beam for three test conditions: MOO's face covering, COTS face covering, and no face covering. MOO may use insights gleaned from this evaluation as part of the information they collect, including trials and tests at other research centers, to assess the design of their face coverings.

D. Summary of Work Performed

The work performed under this project was broken into several tasks that began with evaluation of face covering tests by other researchers and ended with software analyses to determine locations and estimates of relative droplet quantities traveling passed the face coverings. The approach used for this testing was based on a combination of methods employed by different

[2] https://ehsdailyadvisor.blr.com/2020/12/astm-developing-nonregulatory-standard-for-face-masks/

researchers and is not considered an exhaustive study, but strives to provide data to assess the current MOO product version compared to COTS face coverings.

Task 1- Solidification of Test Plan and Ordering of Equipment

GIS reviewed several articles related to formation of droplets and visualization of droplets expelled passed face coverings during simulated coughs. Then the team borrowed aspects of the methods previously used to develop a modified approach, which provided quantitative estimates for expelled droplets. Once the test plan was reviewed with MOO, GIS ordered the appropriate supplies including a line laser, camera, lens, bellows, relays, and solenoid valves. GIS also ordered a COTS face coverings to use as a baseline. A room without windows was chosen for the testing, and the supply and return air ducts to the room were sealed to provide still ambient air for consistency in this side-by-side comparison. The room size was approximately 4.2 meters wide by 4.5 meters deep by 5.5 meters high.

Task 2 – Preparing Testing Environment

GIS prepared the testing environment for this experiment based on the agreed upon test plan from Task 1. This report section provides a high-level description of the setup used to evaluate the face coverings in a side-by-side comparison. Due to the number of unknown factors and lack of industry standards in the testing of community face coverings, GIS applied best practices for the testing process based on information in recently published articles. Description of the setup is separated into the following paragraphs by the function of components.

Droplet Generation: The droplet generator fabricated for the tests used publications by Lindsley et. al.[3] and Verma et.al.[4] as guidance and included modifications to meet the scope of this project. The authors noted their setups provided air flow profiles similar to portions of a human cough, but the setups did not produce the full size range of human cough droplets nor duplicate exact air flow rates. Additionally, human coughs are typically warmer than the surrounding air making them buoyant. The liquid for the comparison tests covered in this report was comprised of ambient temperature water, hence there was a difference in both quantity, size, and motion of the droplets compared to a human baseline. Droplets produced by the droplet generator in the present work were estimated to be less than 10 µm in diameter, as determined through imaging at the minimum

[3] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4615563/
[4] https://aip.scitation.org/doi/full/10.1063/5.0016018

working distance of the camera lens to get the greatest resolution. The droplet generator was pneumatically actuated and controlled through digital outputs of a microcontroller. The average cough rate was 1.5 liters per second with a volume of 3.6 liters, as calculated for this setup.

Mannequin Head: The mannequin head used in the setup was additively manufactured based on a modified computer model of the Medium Symmetry headform from The National Institute for Occupational Safety and Health[5]. The head was modified to create openings for the mouth and connection of the droplet generator, and an attachment plate was added at the neck. The head was fabricated by MOO using a fused deposition modeling (FDM) printer and it had a circular opening made to fit a ¾ inch PVC pipe used for the mouth to provide a similar opening area as measured during a human cough[4]. The horizontal axis of the mouth was approximately 1.6 meters from the floor.

Laser and Camera: A 40mw green line laser (532nm) was used to generate a light plane and was moved relative to the mannequin head for the various videos. A 20 megapixel monochrome camera with 35mm lens was used to capture videos of each test, and it was also moved and focused for the various test views.

Face Coverings: The model of the MOO face covering was specified as “Paper Face Mask by MOO production version approved December 1, 2020” by MOO and had printing on the outside. Minimal stretch of the ear loops on the MOO face coverings was used to obtain a tight fit. The COTS face covering was a Halyard model 47080 three-layer, procedure mask with a nose piece that was formed against the mannequin head for each test. A new face covering was used after each change in the setup.

[5] https://www.cdc.gov/niosh/data/datasets/rd-10130-2020-0/default.html

a) b)

Figure 1 - Face Coverings: a) MOO and b) COTS

Task 3 – Development of Software Algorithm

A software algorithm was developed to identify and quantify the areas of illumination that were recorded as droplets passed through the laser plane. The videos were captured in grayscale, with pixel intensities ranging from 0-255. The intensity levels for the activated pixels in each frame of a video were summed to obtain an overall brightness level for the frame. Due to reflected light and imperfect blackout conditions, a baseline value of the brightness level was computed for each video based on the first video frame, before the droplet expulsion. The baseline brightness level was subtracted from each subsequent frame to approximate the total illumination due to droplets only. Pixel intensity was used as a method to acquire information related to multiple droplets being within the thickness of the laser plane during the exposure time. The algorithm used open source Python libraries, including OpenCV.

Task 4 – Evaluation of Tests

GIS executed the test plan from Task 1 and captured multiple videos of each test condition. Two studies were performed, with the first creating a partial cube around the mannequin head formed by laser light for four views. The tests for each view (Front, Top, Bottom, Side) were split into two groups and each group included a set of three consecutive videos for the MOO, COTS, and no face covering tests. The relative order of the face coverings was varied from group to group. Aside from the change of face coverings, the test setup remained the same for each view. The test head, laser position, and camera positon were changed between views. The lens focus was also checked and adjusted for each view. The Front view was defined as having the laser plane perpendicular to the axis of the mouth at a distance of 18mm from the nose, the Side view was with the laser parallel to the ear and offset by 20mm, the Top view was above the top of the head by 3mm, and the Bottom view was with the laser plane 32 mm below the chin.

The second study captured videos of a profile view, and a Front view having a greater offset of 0.6m to the mannequin head. The camera was manually moved vertically and horizontally for the Front view while remaining perpendicular to the laser plane in order to capture an area of approximately 0.9 meters by 0.9 meters that was centered on the test head. This effectively created a stitched together image that captured a larger area through multiple videos while having similar resolution to the first study. The profile videos were captured for each face covering condition for visualization purposes to show the movement of the droplet plume in still air.

Task 5 – Conduct Analysis

GIS used the algorithm programmed in Python under Task 3 to process the videos from the tests to provide a relative estimate of the droplets passing through the laser planes. The data captured per view from both groups of three videos was averaged for each of the face coverings. Additionally, the data was checked against the assumption of a normal distribution then a statistical test was performed to determine the observed significance level for the null hypothesis where two sets of tests were assumed to be from the same distribution.

E. Results

After capturing the videos of all of the tests, the software algorithm was used to check the results for outliers or errors in the setup during testing. Due to the small droplet sizes, visual enhancements were performed in the algorithm to allow software users to identify the droplets being evaluated by the algorithm. The frames were then processed with the algorithm to provide values for overall brightness to aid in comparisons between face coverings. Representative images for each face covering were captured for this report, refer to Appendix A. One video from the COTS tests was removed from the analysis for the Bottom view due to change in position of the face covering during the testing.

Figure 2 - Front View of No Face Covering Test. A) Video frame during droplet expulsion with no face covering.

Front View: The tests of the Front view for the no face covering condition showed the highest overall relative brightness level as computed by the software algorithm. Visually, the expelled droplets passing through the laser plane were detectable without software enhancements, refer to Figure 2. In contrast, the MOO and COTS face coverings were difficult to detect in this test and the overall brightness level computed by the software algorithm showed lower values than the no face covering condition.

Top View: The tests of the Top view for the MOO face covering showed the most droplets, which are hypothesized to come from gaps around the nose, refer to Figure 3. Similarly, the COTS face covering showed evidence of droplets in the Top view. Given the direction and velocity of the droplets from the mouth of the mannequin head, there was relatively little indication of droplets passing through the top laser plane when no face covering was applied (i.e. droplets were expelled forward).

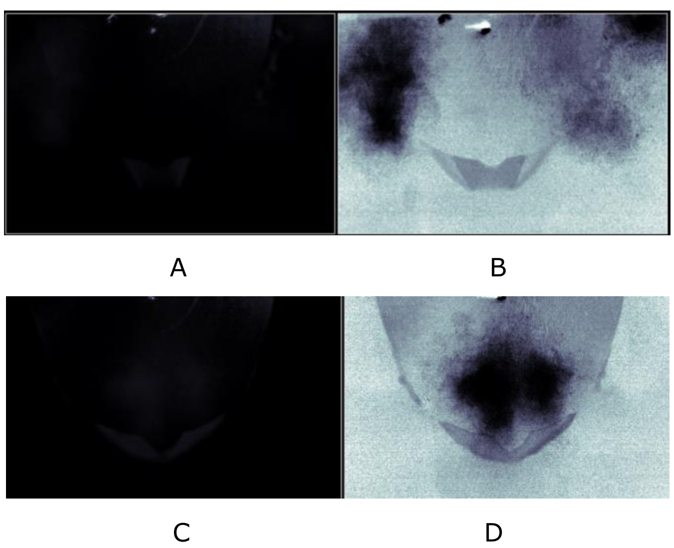


Figure 3 – Top View of Face Covering test. A) Video frame during droplet expulsion with MOO face covering. B) Same image as A, but with contrast enhancement - having black plumes form on the periphery. C) Video frame during droplet expulsion with COTS face covering. D) Same image as C, but with contrast enhancement - having a black plume form near the center.

Bottom View: Tests of the Bottom view also indicated areas of droplet travel for the MOO face coverings, refer to Figure 4. The COTS and no face covering tests showed fewer droplets than the MOO face covering, both visually and in the computer analysis. There was more reflected light in the Bottom view of this test setup due to the laser plane intersecting the neck of the mannequin. This reflected light may have factored into the statistical analysis, which indicated the null hypothesis (values are from the same distribution) could not be rejected at a 95% confidence interval.

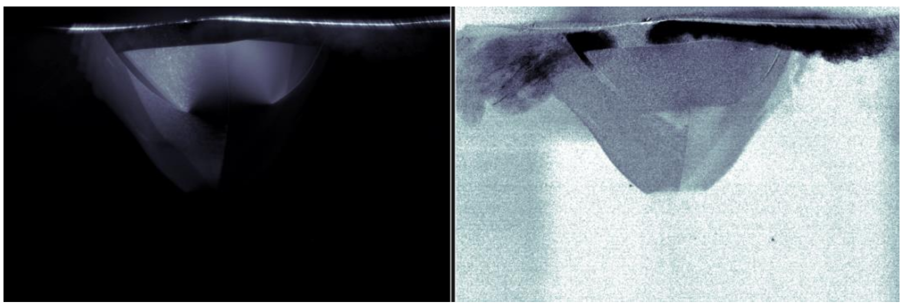


Figure 4 – Bottom View of MOO Face Covering test. Left image is of a video frame during droplet expulsion. Right image is the same frame with enhancement of contrast – having black plumes form at the upper edge of the image.

Side View: Tests of the Side view indicated the primary route of droplet travel for the COTS face coverings in this test, refer to Figure 5. Although the COTS face covering was in contact with the mannequin's cheek during setup, the pucker of the material is believed to have provided a pathway of less resistance for the droplets. The MOO and No face coverings showed less evidence of droplets in this view. Given the geometry of the Medium Symmetry mannequin head, only one side of the head was tested.

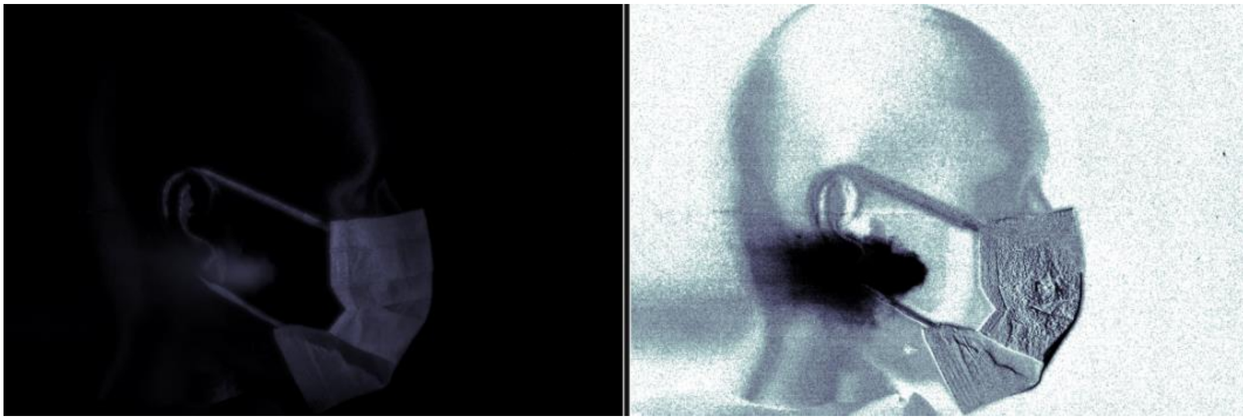


Figure 5 - Side View of COTS Face Covering test. Left image is of a video frame during droplet expulsion. Right image is the same frame with enhancement of contrast – having a black plume form near the ear.

Study 1 Comparison: Given the fit of the face coverings and the setup, there was variation between tests as expected. Statistical tests performed on the data suggested the results from the three face covering conditions were statistically different for the Front, Sides, and Top views at a 95% confidence interval for the limited number of samples tested. The statistical test for the Bottom view did not provide enough evidence that the data for the three face coverings were from different distributions, refer to Table 3. The results from the Side view in the table were doubled due to the assumption of symmetry. Given similar working distances for the camera lens to the laser for each view, the values for each face covering were summed for a Total value. This Total value was considered to be directionally accurate given potential differences in the factors for each view; therefore, caution is advised if trying to extract conclusions from these values. The relative values for the individual views were considered to be more informative as to areas for potential improvement of the face covering designs.

Table 3 – Results Table for the test conditions

	Overall Relative Pixel Brightness (%) [Mean]				
	Front	**Side (x 2)**	**Bottom**	**Top**	**Total**
No Face Covering	10.7	0.06	0.23	0.01	11.0
MOO Face Coverings	0.03	0.50	1.53	3.80	5.9
COTS Face Coverings	0.14	3.58	0.65	1.67	6.0
Statistical tests:					
P-value MOO vs No	5E-8	0.02	0.06	0.002	0.002
P-value MOO vs COTS	0.01	6E-4	0.17	0.006	0.89

P-value No vs COTS	4E-8	5E-4	0.14	0.005	1E-4

Study 2 Comparison: The tests for the Front view of the mannequin head were repeated, but with a laser offset from the head of 0.6 meters. This was done to obtain information related to the distance the droplets traveled when there was no measurable air flow in the room; however, caution is advised when evaluating these values because air flow is an important factor in droplet dispersion distance from an actual cough[6]. In order to capture a relatively large area, 0.9 x 0.9 meters squared, the camera was moved to 21 different positions to capture the videos in order to stitch together one larger video, while maintaining the resolution used in the previous trials. The results indicate a greater overall brightness level for the tests without a face covering compared to the tests with the MOO and COTS face coverings, refer to Table 4.

Table 4: Summary of Test Results with Laser Plane 0.6 meters from the Head – Images Stitched together to effectively capture a 0.9 x 0.9 meter^2 Area

	Overall Relative Pixel Brightness (%), Front View* [Mean]
No Face Covering	2.2
MOO Face Covering	0.14
COTS Face Covering	0.18

*without measurable air flow that may affect droplet movement

F. Summary

The objective of this project was to perform a side-by-side comparison of relative scatter of light from droplets expelled through a laser beam for three test conditions: MOO's face covering, a commercial of the shelf (COTS) face covering, and no face covering. Overall relative pixel brightness was used as a proxy for measurement of droplets in still air and the test results provided insight into areas for further evaluation of face covering designs.

While the results are specific for the test conditions and setup used in this project, the MOO face covering appeared to reduce droplets traveling through the laser plane when positioned in front of the mannequin head with no measureable air movement compared to no face covering and COTS face coverings. The MOO face covering showed higher relative brightness levels for the

6 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7239332/#:~:text=Without%20the%20surrounding%20wind%20speed,may%20travel%20slightly%20further%20longer

Top and Bottom views compared to the other face covering conditions, indicating more droplets were passing through the laser plane. In contrast, the COTS face covering showed the highest relative brightness levels for the side view.

The findings of this study should not be considered representative of use in real world settings and should only be used as a relative indicator of effectiveness. Additionally, the findings of this evaluation should not be generalized to other face coverings. Separate studies would need to be conducted to determine the significance of the results relative to source control and personal protection[7]. Aerosolized particles that may be a transport mode for infection agents were not evaluated in this project and the tests do not attempt to inform transmission routes due, in part, to the still ambient air conditions used in these tests[8]. MOO may choose to use these results as part of the information they collect to assess the design of their face coverings, including tests at other research centers that have been performed.

[7] *https://www.cdc.gov/coronavirus/2019-ncov/more/masking-science-sars-cov2.html*

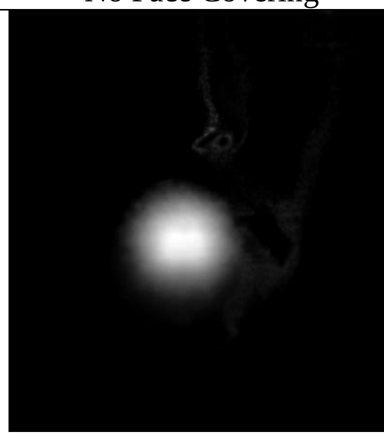
[8] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7239332/#:~:text=Without%20the%20surrounding%20wind%20speed,may%20travel%20slightly%20further%20longer

G. Appendix

This appendix provides images selected from each view for the face coverings that are visually representative of the tests performed. Many images also show reflected light from the mask or test setup, which may make interpretation of the images more difficult when evaluated by eye. A short description is provided to aid with the interpretation of the images.

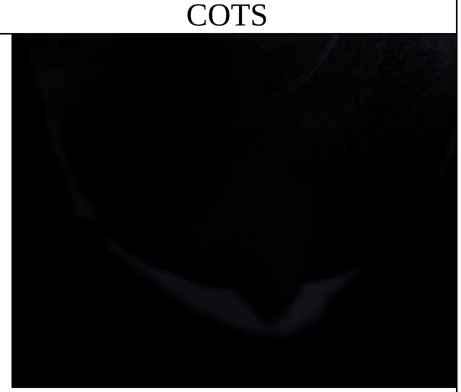
Front View

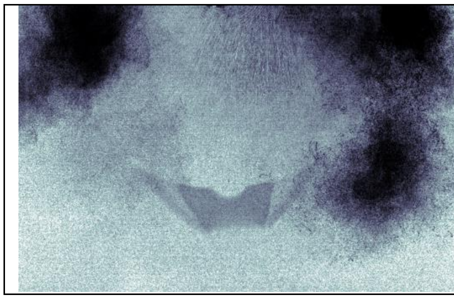
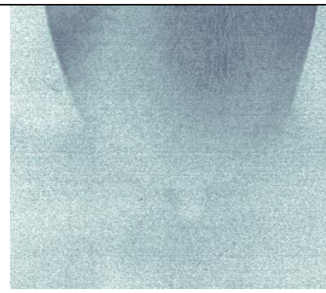
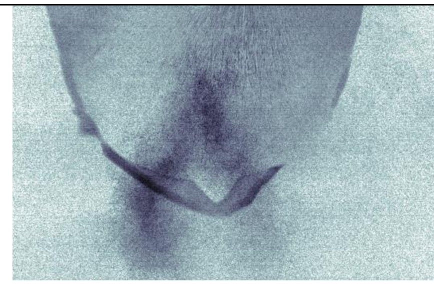
Without the aid of the software algorithm it is difficult to visually detect any droplets in the MOO and COTS images. However, light from the droplets was easily seen in the No face covering images.

MOO	No Face Covering	COTS
		

Top View

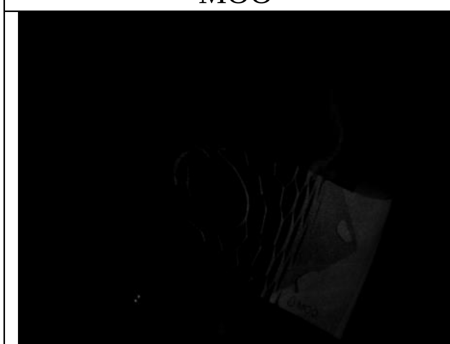
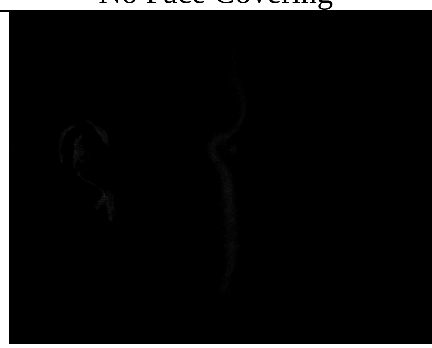
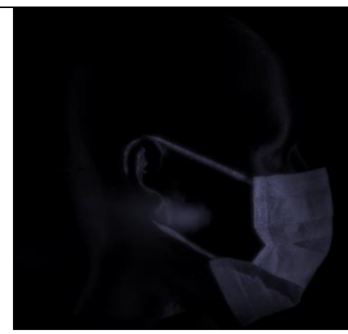
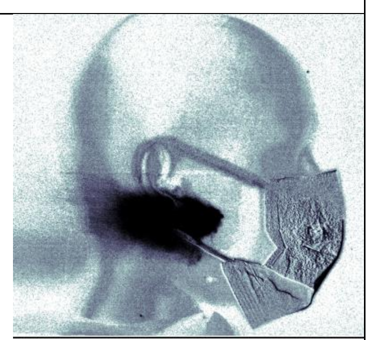
The laser plane was furthest away from the mouth in the Top View tests; therefore, droplets appeared to be spread out more and harder to detect without the aid of the software. The lower set of images are of a similar frame, but with enhancement of contrast for the viewer.

MOO	No Face Covering	COTS
		

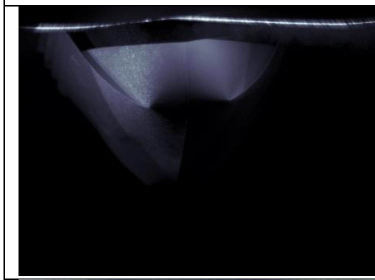
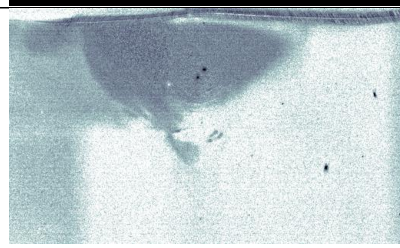
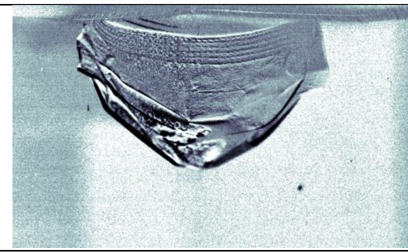
<u>Side View</u>

Light from the droplets is detectable by eye for the COTS face covering in the Side view; however, it is difficult to discern droplets in the other two images. The lower images are of a similar frame, but with enhancement of contrast for the viewer. In the enhanced frame, there appear to be several larger droplets expelled from the MOO face covering near the ear.

MOO	No Face Covering	COTS
		
		

<u>Bottom View</u>

It is difficult to visually see droplets from the COTS and No Face Covering tests; however, the MOO test showed visible reflections from droplets. There appeared to be several larger droplets expelled from the COTS and no face covering tests. The setup had more reflected light than other views. The lower images are of a similar frame, but with enhancement of contrast for the viewer.

MOO	No Face Covering	COTS
		
		

Profile View

These profile images are for information only, but provide a prospective on the motion of some of the droplets detected in a single laser plane.

MOO	No Face Covering	COTS