PAPER

The Use of a UVC Lamp Incorporated With an ROV to Prevent Biofouling: A Proof-of-Concept Study

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ABSTRACT

A proof-of-concept study was designed to investigate using an Ultraviolet C (UVC) lamp mounted on a hull-crawling remotely operated vehicle (ROV) to prevent biofouling on a ship hull. A wheeled cart with a UVC lamp was built to expose two large test panels to UVC. The test panels were coated with an ablative copper antifouling and a silicone fouling release coating, and these were immersed in seawater at Port Canaveral, Florida. Three exposure frequencies (once a week, twice a week, and three times a week) and two dosages (8 and 16 s of UVC exposure) were tested. UVC was effective at preventing biofilm growth during the first 2 weeks of UVC treatment but was unable to prevent increased fouling growth as time progressed. It appears that an increase in UVC intensity and duration of exposure would be needed to prevent fouling growth especially during high-fouling seasons or that UVC exposure would need to be combined with another fouling prevention practice, such as mechanical wiping, to be more effective.
Keywords: UVC, ROV, grooming, biofouling, marine coatings

Introduction

Biofouling, the accumulation of organisms on a submerged surface, has been problematic for the shipping industry throughout history as it leads to many financial and functional setbacks. The process of biofouling occurs in multiple steps where biofilm formation can be thought of as the initial phase (Chambers et al., 2006; Lejars et al., 2012). Larvae can be attracted or even repelled by chemical cues of the biofilm, but once the larvae settle on the surface, they can establish themselves and grow into fully developed macrofouling organisms such as barnacles, tubeworms, or green algae (Chambers et al., 2006; Lejars et al., 2012).

As biofouling accumulates on a ship hull, there is an increase in frictional drag, fuel consumption, greenhouse gas emissions, and operational costs for a vessel (Schultz et al., 2011; Swain et al., 2007). The most common method to prevent biofouling settlement is through the application of fouling control coatings. There are two main classes of fouling control coatings: biocidal and fouling release. Biocidal coatings contain heavy metals to deter fouling settlement, but often, these heavy metals are leached into the aquatic environment (Swain, 1999, 2010). Meanwhile, fouling release coatings contain silicone oils designed to alter the adhesion strength of fouling organisms (Kavanagh et al., 2001; Swain, 1999, 2010). The fouling release coating does not release heavy metals into the environment but requires a vessel to move at certain speeds for hydrodynamic removal of biofouling organisms (Schultz et al., 1999) or by way of mechanical cleaning on the ship hull. Both coating types will become fouled when a ship is at rest for extended periods of time (Swain, 1999, 2010) and the search for environmentally effective solutions is still ongoing.

Grooming is a proactive practice to extend the life of these fouling control coatings and reduces fouling accumulation. It is the gentle, habitual, mechanical maintenance of a ship hull to maintain a hull free of fouling and particulate debris without damaging the coating (Tribou & Swain, 2010, 2015, 2017). This is done primarily by a remotely operated vehicle (ROV). Recent research has shown that grooming by applying a frequent and gentle cleaning of fouling control coatings using rotating brushes will successfully control fouling (Hearin et al., 2015; Tribou & Swain 2015, 2017).

Ultraviolet C (UVC) light is also being used in the marine environment as a biofouling prevention tool. It is well known as a method to kill germs or sanitize surfaces in the medical field. UVC is the most germicidal part of the

UV spectrum as it damages the chemical bonds in DNA and RNA (Bak et al., 2009; Salters & Piola, 2017). A dose between 10 and 300 J/m^2 can kill 99.9% of planktonic bacteria, with this variation in range a result of different species of bacteria (Bak et al., 2009; Qiu et al., 2004; Salters & Piola, 2017). UVC has long been used in the offshore oil and gas industries to control microbes in seawater injection systems, and it has been applied as a point source to prevent fouling of instrumentation (Hijnen & Jongerius, 2018; Patil et al., 2007; Salters & Piola, 2017). UVC LEDs have also been placed in a clear silicone coating to provide a fouling free surface for areas such as within a sea chest (Salters & Piola, 2017). Recently, UVC lamps installed at different distances from a surface, utilizing various UVC exposure times, and applied to fouling control coatings have also proven effective against biofouling accumulation (Braga et al., 2020; Hunsucker et al., 2019).

Hearin et al. (2015, 2016) found more frequent grooming is required to maintain a fouling-free surface during warmer months in a subtropical environment. The same study found that less routine grooming would allow for the development of biofilms during the fouling seasons. However, UVC has been found to prevent biofilm buildup on fouling control coatings (Hunsucker et al., 2019) even during some of the higher fouling periods. Thus, a study was designed to determine if grooming and UVC could be used to reduce the frequency of grooming needed during high-fouling seasons. Before a full-scale study could be designed, it was important to understand if the UVC was indeed having an effect on the biofouling, without the use of brushes typically utilized in grooming practices (Hearin et al., 2015; Hunsucker et al., 2018). To determine if the UVC was an effective component of grooming, a proof-of-concept study applied UVC on two fouling control coatings by an ROV at a frequency that has previously been shown to prevent biofouling (Hearin et al., 2016).

Methods

Large-Scale Seawater Test Facility

All testing was performed at the Center for Corrosion and Biofouling Control large-scale seawater test facility (LSTF) located in Port Canaveral, FL (28°24'31.01"N, 80°37'39.54"W). The test site has an average salinity of 34 ± 2 ppt with an average water temperature of 27°C ± 2°C. High fouling occurs at the test site year-round, with individual fouling organisms displaying seasonality. During the warmer months of June-August, barnacles, calcareous tubeworms, and tunicates dominate the biofouling community. The abundant fouling organisms during the cooler months of December-February are arborescent bryozoans and biofilms.

Grooming tests were conducted on two floating steel test panel assemblies. Test panels consist of a 4.6 m × 2.4 m steel plate welded to a 0.76-m diameter pipe for flotation (Hearin et al., 2015, 2016). One steel panel was coated with an ablative copper antifouling coating, and the other was coated with a silicone fouling release coating (Hearin et al., 2015, 2016).

Push Underwater Grooming Tool With Ultraviolet Light

A hand-operated UV grooming tool was designed based off the Push Underwater Groomer (PUG) used in Hearin et al. (2015) and Hunsucker et al. (2018). There were four basic components to the UV grooming tool (PUG UV): (1) a three-wheeled PVC chassis and a telescoping pole for manual control, (2) a 25-W UVC lamp (254 nm) and a 203 mm × 432 mm aluminum reflector, (3) an impellor that provided suction for attachment onto the test surface, and (4) an electric motor control box and a UVC lamp power supply (Figure 1). The UVC lamp was held 25 mm from the surface

FIGURE 1

The components of PUG UV and its control box.

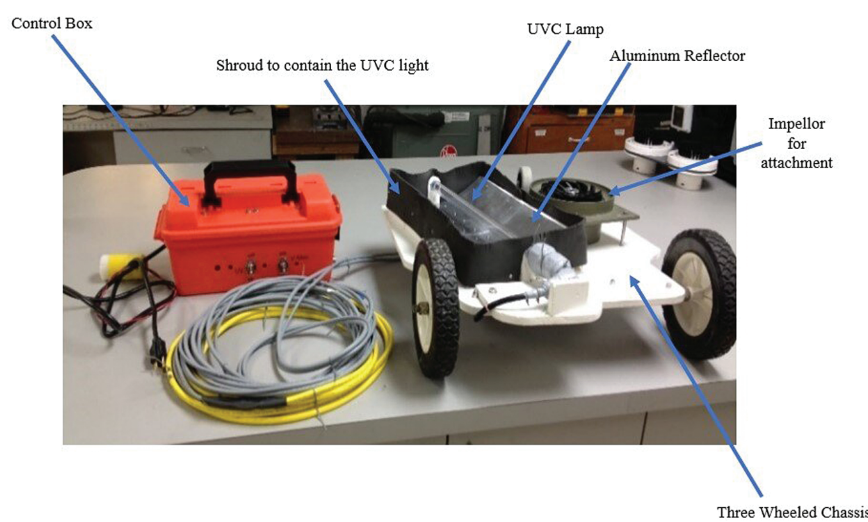
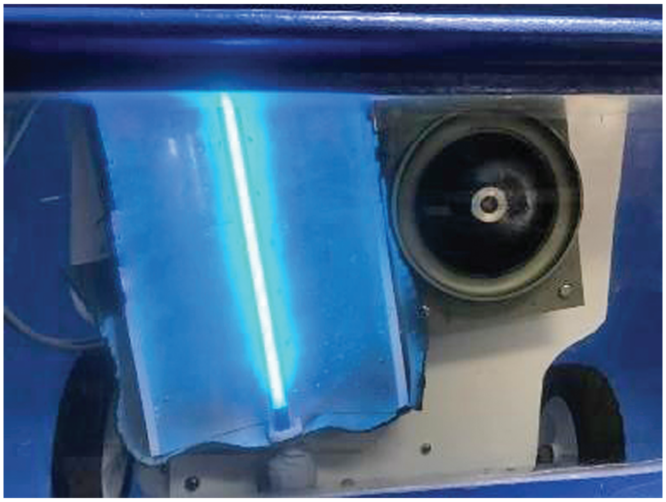


FIGURE 2

The UV grooming tool being tested in a tank before deployment to ensure functionality.



being groomed. The lamp itself had dimensions of approximately 432 mm × 25 mm, and the aluminum reflector was used to reflect the light to the surface being groomed (Figure 2).

The amount of UVC hitting the surface was calculated by taking average UVC transmission values at the Port Canaveral test site over a 3-month period (May-July)with a UVC sensor (Solar Light PMA 2100 Photometer and UVC Sensor PMA2122). The amount of UVC hitting the surface during this experiment was estimated to be 11.46 $\frac{W}{m^2}$.

UV Exposure Design

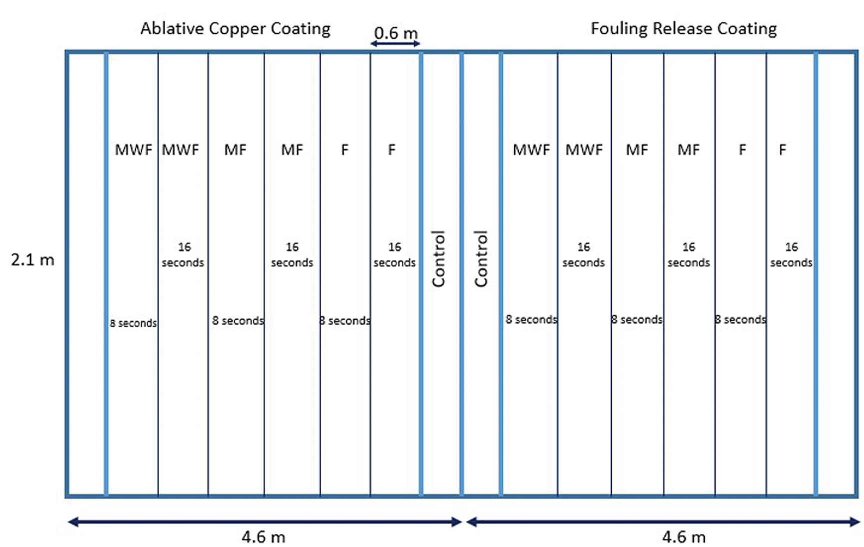
Each steel panel was divided into six 0.61 m × 2.1 m sections to allow for both the dose and the grooming frequency to be tested (each section consisted of a different treatment of frequency and dose) (Figure 3). The grooming frequencies selected were once a week (F), twice a week (MF), and three times a week (MWF), and an ungroomed control based on previous experiments conducted at the LSTF (Hearin et al., 2016). In addition, each frequency was also subjected to one of two dosage treatments: 8 s of UVC exposure (achieved with 2 passes of the UV grooming tool) and 16 s of UVC exposure (achieved with 4 passes of the UV grooming tool). This was achieved via the grooming tool moving at a rate of 0.1 m/s over the entire test panel. Testing was conducted over the course of a month (June-July 2017) during the high-fouling season, and inspections were performed every 2 weeks.

Biofouling and Statistical Analysis

Underwater images were taken before UVC exposure, after 2 weeks of UVC exposure, and after 4 weeks of UVC exposure to determine biofouling coverage and community composition. Each photograph was taken at 0.3-m increments (from 0.6 to 1.8 m) to cover the entire test panel. The 0.3- and 2.1-m sections of the test panels were excluded. These depths correspond to the shallowest and deepest sections of the panel and could have had other variables impacting their fouling community structure (e.g., fouling edge effects from the pipe brackets welded to the panels). Coral Point Count with Excel extension software (CPCe; Kohler & Gill, 2006) was used to assess the fouling accumulation for each coating. The CPCe visual assessment distributed 50 random points across each photograph. There was a total of 70 photographs used for analysis (14 test sections with five photographs each). Total percent fouling

FIGURE 3

A diagram of the large-scale steel test panels and where the UV grooming frequencies and dosages were applied.



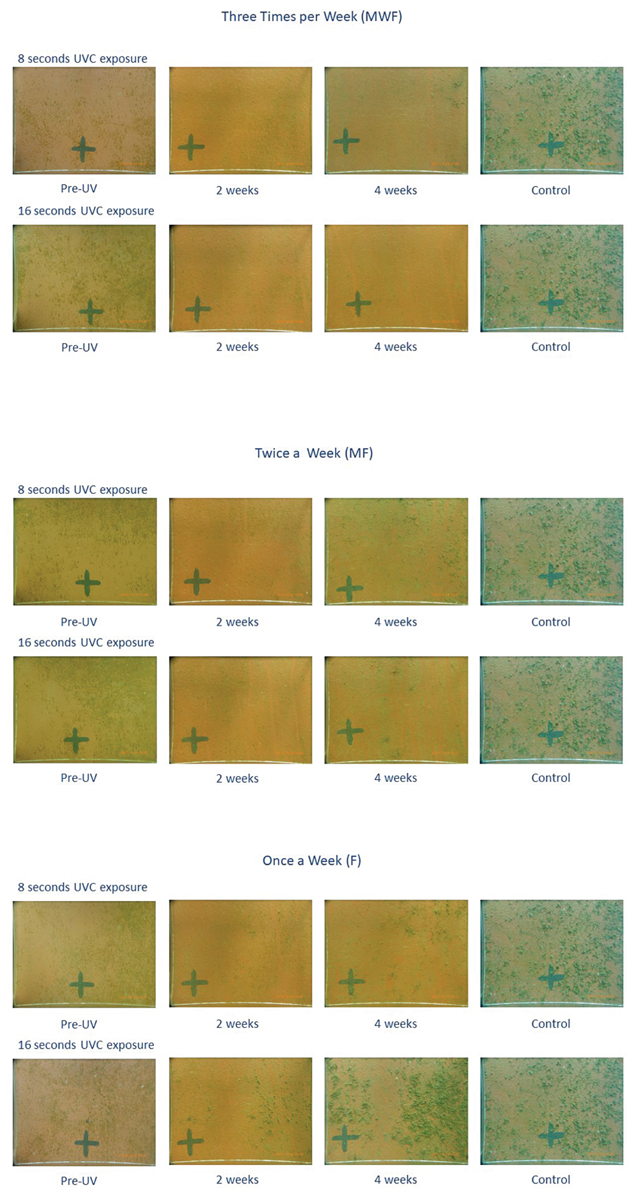
coverage for each image was noted, and individual organisms were placed into their functional groups (e.g., biofilm, barnacles, encrusting bryozoans). The CPCe program calculates the percent cover for each of these functional groups based off the user input from the 50 randomly distributed grid points. The data from each of the photographs were averaged together as a total to be used for each panel. Then, a repeated measures analysis of variance (ANOVA) was run through the statistical analysis program R (R Core Team, 2018) to compare the fouling coverage for the different grooming frequencies, dosages, and coatings. If the assumptions of the test were not met for normality, the data was transformed. If the repeated-measures ANOVA indicated that there was a significant difference in the dataset, a Games-Howell test was run to identify where these differences were coming from.

Results

After 2 weeks of UVC exposure, both the copper and fouling release coatings had a decrease in biofilm coverage when compared to the pre-UV assessment. The control surfaces, on the other hand, had a slight increase in biofilm coverage (Figures 4 and 5). However, after 4 weeks of UVC exposure, both coatings appeared to have had an increase in biofilm growth when compared to the 2-week assessment (Figures 4 and 5). At this time, all treatments of the ablative copper coating and the fouling release coating were fouled with biofilms (Figures 4–6). However, for the fouling release coatings, the control surfaces and the sections that had a shorter frequency of UVC exposure (e.g., once and twice per week) did show a small percentage of macrofouling coverage.

FIGURE 4

Representative photographs of the copper ablative coating during the course of the study: before being subjected to UVC in different doses (pre-UV) and after UVC exposure (2 and 4 weeks).



This trend was also seen on the copper coatings for the once-per-week treatment. There was a significant difference present with time (pre-UV, 2 weeks, and 4 weeks). The decrease in biofilm coverage during the first 2 weeks of UV exposure was significant, demonstrating that UVC was effective at preventing biofilm growth (Table 1). There was a significant increase in biofilm coverage between the pre-UV and 4 weeks of UVC exposure, as well as between the 2 and 4 weeks of UVC exposure, suggesting that after 2 weeks, the UVC alone was not enough to prevent continued biofilm accumulation.

Two different types of coatings were used in this study, an ablative copper antifouling and a silicone

FIGURE 5

Representative photographs of the fouling release coating during the course of the study: before being subjected to UVC in different doses (pre-UV) and after UVC exposure (2 and 4 weeks).

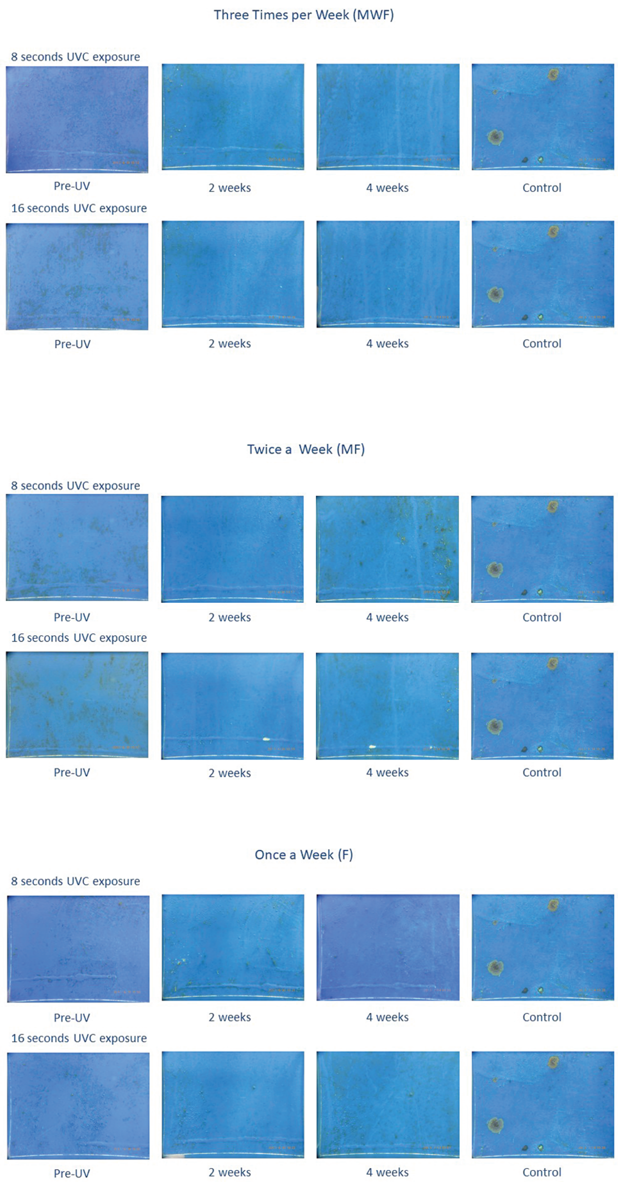
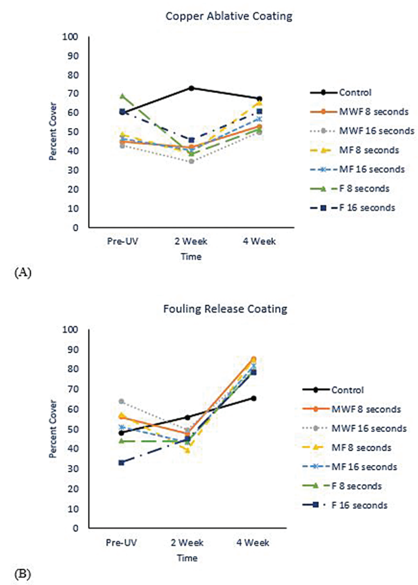


FIGURE 6

Relative abundance of fouling accumulation for the copper (A) and the fouling release coatings (B) with respect to UV grooming frequency and dosage over time.



fouling release. Both coatings demonstrated the same trend, with a decrease in biofilm coverage after 2 weeks of UVC exposure, which then increased in coverage after another 2 weeks of exposure (Figure 6). At the end of the testing, the biofilm coverage was higher on the fouling release coating compared to the antifouling coating. Both control coatings had a slight accumulation of hard fouling by the 4-week period, which was not seen on all of the UVC treatments. Statistical analyses determined the fouling difference between coatings to not be significant (Table 1).

The copper coating appeared to have less biofilm accumulation with the highest dose and frequency (three times a week with 16 s) of UVC exposure (Figure 6). This was not the case for the fouling release coating, where frequency and dose did not have much of an impact on the accumulation of biofilms during this study (Figure 6). Overall, no significant difference in biofilm growth was found between UVC exposure frequency (Table 1) and dose (Table 2). The timeframe of pre-UV, 2 weeks, and 4 weeks of UVC exposure are the only factors that could be clearly identified as having a significant difference.

Discussion

The application of UVC was effective for a short term and then was unable to keep up with the fouling pressure regardless of coating type, frequency, or dosage. This indicates that using UVC exposure alone (as in the method described here) to control fouling on a large-scale surface

TABLE 1

The repeated-measures ANOVA results comparing the percent cover of biofilm accumulation for both coatings tested after 1 month of UV grooming.

Source of Variation	*df*	SS	MS	*F*	*p*
Time (pre-UV, 2 weeks, 4 weeks)	1	0.0947	0.09473	8.683	0.00628
Exposure frequency (MWF, MF, F)	2	0.0001	0.00006	0.005	0.99477
Coating (copper, fouling release)	1	0.0406	0.04057	3.719	0.06365
Time × Exposure Frequency	2	0.0021	0.00103	0.095	0.90986
Residuals	29	0.3164	0.01091		
Total	35	0.4539			

would require exposure times that are much higher. Previous studies have found UVC to prevent growth on fouling control coatings by applying frequencies such as 1 min/6 h, 1 min/day, and continuous exposure (Hunsucker et al., 2019). During the experiment discussed herein, the exposure frequencies are the equivalent of 8 or 16 s per day. This means that the “three times a “week exposure was 24 s/week for the 8-s dosage and the 48 s/week for the 16-s dosage. Clearly, the results demonstrate that these exposure frequencies were not effective enough to prevent fouling for the duration of this study. While continuous exposure on the ship hull via the ROV would not be feasible, an increase in frequency and dose (higher than what was used during this experiment) may demonstrate to be more effective on a large-scale surface.

Statistical differences were not seen in the fouling accumulation between the copper and fouling release coatings. Both the copper and fouling release coatings did not have any signs of damage during this experiment, but Hunsucker et al. (2019) and Braga et al. (2020) demonstrated that, while continuous UVC exposure is effective at preventing and removing an established biofilm community, it can cause damage to coatings. Continuous UVC, applied at a distance of 25 mm from a surface, resulted in visible changes to an ablative copper coating after 1 month with a decrease in coating condition over the 4-month experiment, possibly due to coating hydrolysis (Hunsucker et al., 2019). Thus, minimizing damage to ship hull coatings must be considered when trying to find an effective UVC exposure time to prevent biofouling.

The large-scale steel test panels were cleaned back prior to this experiment, but some biofilm was still

TABLE 2

The repeated-measures ANOVA results determining if UVC exposure frequency and dose had a measurable effect on biofilm growth prevention.

	Source of Variation	*df*	SS	MS	*F*	*p*
Copper coating	Time (pre-UV, 2 weeks, 4 weeks)	2	282.0	141.0	6.793	0.018865
	Exposure frequency (MWF, MF, F)	2	848.2	424.1	20.432	0.000718
	Dose (8 s, 16 s)	1	9.5	9.5	0.457	0.517957
	Time × Exposure Frequency	4	318.0	79.5	3.831	0.050227
	Residuals	8	166.0	20.8		
	Total	17	1623.7			
Fouling release coating	Time (pre-UV, 2 weeks, 4 weeks)	2	1.435	0.717	8.240	0.0114
	Exposure frequency (MWF, MF, F)	2	18.619	9.310	106.949	<0.05
	Dose (8 s, 16 s)	1	0.042	0.042	0.477	0.5093
	Time × Exposure Frequency	4	1.505	0.376	4.323	0.0374
	Residuals	8	0.696	0.087		
	Total	17	22.297			

present before UVC exposure. This biofilm was not able to be removed without damaging the coatings. This also led to variation in the pre-UV exposure coverage but was considered to be an additional control for the experiment to ensure that any changes in fouling coverage could be accounted for right from the beginning of UVC exposure. It was positive that UVC was able to maintain or reduce this biofilm level during the first 2 weeks of exposure. Recently, Braga et al. (2020) applied continuous UVC to an inert surface and successfully reduced the accumulation of an established biofouling community, which included biofilms. Thus, it is possible to remove an established community with continuous exposure for a month; however, there are uncertainties as to the minimum frequency and dose needed to reduce just a light biofilm layer, such as what was present during the pre-UV. While continuous UVC may be applicable in certain settings, such as in sea chests, the minimum application would be more appropriate for an ROV passing over a ship in port.

A UVC light source may have the potential to act in conjunction with brush grooming methods (such as those described in Hearin et al. 2015, 2016). The prevention of fouling by a UVC/brush tool may provide a more effective hull fouling management system than just the UVC application alone, but this would need to be investigated further. More research would also need to be performed to test the energy consumption required for UVC to be feasibly incorporated into a grooming tool.

Conclusion

This experiment was designed as a proof-of-concept study to determine if an ROV incorporated with a UVC lamp would be effective at preventing biofilm growth when using specific UVC exposure frequencies (three times a week, twice a week, and once a week) and dosages (8 and 16 s of UVC exposure). The results indicate that, after 2 weeks of UVC exposure, the methods used here were effective at preventing biofilm growth; however, as time progressed, UVC exposure was unable to manage the continued growth. Since this was a proof-of-concept study, the experiment was terminated when this was discovered. Further research should continue to investigate how various UVC exposure times influence fouling growth and to determine if UVC used in conjunction with other fouling prevention practices, such as brush grooming, is more effective than utilizing UVC or the prevention method on its own.

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