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Potential Repair of *Escherichia coli* DNA following Exposure to UV Radiation from Both Medium- and Low-Pressure UV Sources Used in Drinking Water Treatment

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The increased use of UV radiation as a drinking water treatment technology has instigated studies of the repair potential of microorganisms following treatment. This study challenged the repair potential of an optimally grown nonpathogenic laboratory strain of *Escherichia coli* after UV radiation from low- and medium-pressure lamps. Samples were irradiated with doses of 5, 8, and 10 mJ/cm^2 from a low-pressure lamp and 3, 5, 8, and 10 mJ/cm^2 from a medium-pressure UV lamp housed in a bench-scale collimated beam apparatus. Following irradiation, samples were incubated at 37°C under photoreactivating light or in the dark. Sample aliquots were analyzed for up to 4 h following incubation using a standard plate count. Results of this study showed that *E. coli* underwent photorepair following exposure to the low-pressure UV source, but no repair was detectable following exposure to the medium-pressure UV source at the initial doses examined. Minimal repair was eventually observed upon medium-pressure UV lamp exposure when doses were lowered to 3 mJ/cm^2. This study clearly indicates differences in repair potential under laboratory conditions between irradiation from low-pressure and medium-pressure UV sources of the type used in water treatment.

In pursuit of alternatives to chemical disinfection in drinking water treatment, there has been increased interest in the use of UV light for this purpose. UV light is considered a viable treatment technology because it has been shown to effectively inactivate pathogens (4) while forming limited disinfection byproducts (21). The effectiveness of UV light in biological inactivation arises primarily from the fact that DNA molecules absorb UV photons between 200 and 300 nm, with peak absorption at 260 nm. This absorption creates damage in the DNA by altering nucleotide base pairing, thereby creating new linkages between adjacent nucleotides on the same DNA strand. This damage occurs particularly between pyrimidine bases. If the damage goes unrepaired, DNA replication is blocked, and this ultimately results in cell death (e.g., see reference 7).

Low-pressure mercury UV lamps have traditionally been used in water treatment. The low pressure applied to the mercury gas inside the lamp (<10 torr) causes sharp emission lines that output at 254 nm (1). Low-pressure lamps are considered germicidal because of this nearly monochromatic emission, which closely corresponds with the associated DNA absorption wavelength. Microbial inactivation and the subsequent ability of certain microorganisms to repair damage following exposure to low-pressure UV irradiation have been well documented (e.g., see references 7 and 10).

Medium-pressure mercury UV lamps have recently been considered an effective alternative to low-pressure lamps. In contrast to low-pressure systems, these lamps have increased pressure on the mercury gas within the lamp (~1,000 torr) (1). The increased pressure and subsequent higher-intensity radiation from the lamp mean that fewer lamps are needed for disinfection (18). Along with an increase in power, the emission lines of the lamp are broadened. Medium-pressure lamps emit over a range of wavelengths ranging from far UV (185 nm) to infrared (1,367 nm) (18). Figure 1 shows an example of the difference in relative spectral emittance between low- and medium-pressure UV lamps at wavelengths between 200 and 400 nm (1). The increased use of medium-pressure UV lamps in water treatment facilities has prompted an evaluation of the relative efficacy of the polychromatic wavelengths for inactivation and potential reactivation of microorganisms.

As a result of exposure to UV radiation from sunlight, many organisms have developed mechanisms to compensate for the damaging effects of UV radiation. These organisms can possess multiple pathways to repair UV-induced DNA damage. Nucleotide excision repair and photoreactivation are two major removal pathways used to correct UV-induced DNA damage (24). Nucleotide excision repair, often referred to as dark repair, is widely distributed and conserved through evolution. This repair process involves the action of more than a dozen proteins that coordinate the removal of DNA damage (7). Aside from dark repair, many organisms repair damage through a process called photoreactivation. This process uses a single enzyme called photolyase to reverse UV-induced damage to DNA. Photoreactivation is a light-dependent process that requires specific wavelengths of light ranging from 300 to 500 nm to complete the repair process (7).

In drinking water distribution systems, treated water can be subjected to long detention times prior to reaching the consumer. During this time, UV-irradiated microorganisms may have the opportunity to carry out dark repair and potentially regrow within the system. However, exposure to light cannot be completely ruled out during treatment or after the water

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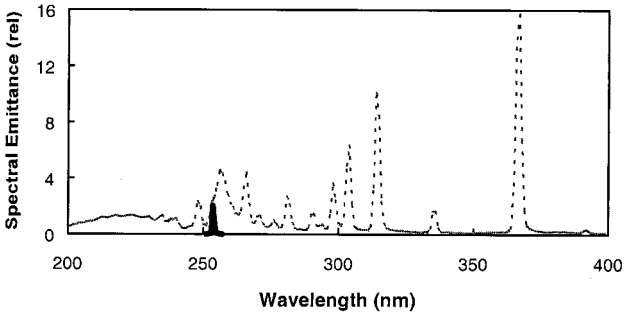

FIG. 1. Comparison of the relative spectral emittance (200 to 400 nm) for low- (——) and medium-pressure (----) UV lamps (reprinted from reference 1 with permission).

TABLE 1. Initial log inactivation of *E. coli* following low- and medium-pressure UV irradiation before repair incubation

UV source lamp	UV dose (mJ/cm^2)[a]		No. of expts	Initial log inactivation (avg ± SD)
	Weighted	Unweighted		
Low pressure	NA	5	3	1.6 ± 0.32
	NA	8	2	4.2 ± 0.27
	NA	10	3	5.0 ± 0.21
Medium pressure	3	4	2	4.7 ± 0.15
	5	6.6	2	4.9 ± 0.71
	8	10.6	2	5.0 ± 0.11
	10	13.3	2	5.2 ± 0.35

[a] NA, not applicable (low-pressure UV doses are not weighted).

reaches consumers. At these times, photoreactivation may have an increased significance. In other areas of water treatment, the issue of photorepair is of greater concern due to increased opportunity for light exposure, for example, in wastewater treatment. Ineffective inactivation of potential pathogens in wastewater treatment will subsequently increase the potential load of pathogenic microorganisms on the watershed and to drinking water intakes. In drinking water treatment systems, reactivation of pathogens over indicator organisms is of primary concern. However, if indicators reactivate, then pathogen numbers might be overestimated.

The overall objective of this study was to compare the repair potential of *E. coli* following both low- and medium-pressure UV exposure. Reactivation studies in the past have focused on DNA repair of microorganisms following UV exposure from low-pressure lamps (11, 12, 22, 23), but to date there has not been documentation of repair potential following exposure to UV from medium-pressure lamps.

MATERIALS AND METHODS

UV source. A bench-scale collimated beam apparatus (Calgon Carbon Corp., Pittsburgh, Pa.) was used to irradiate the samples in this study. This apparatus contains interchangeable low-pressure (12 W) and medium-pressure (1 kW) mercury UV lamps. The selected UV lamp is housed above a polyvinyl chloride collimating tube (93 cm) that aids in focusing the UV beam on the sample to be irradiated.

For both types of lamps, the irradiance was measured with a radiometer (model 1L 1700; International Light, Newburyport, Mass.) equipped with an SED 240 UV detector. This instrument was calibrated to the standards of the U.S. National Institute of Standards and Technology.

Medium-pressure dose determination. The UV dose (mJ/cm^2) was determined by multiplying the average irradiance (milliwatts per square centimeter) in the liquid containing the sample by the irradiation time (seconds). Determining UV dose from a medium-pressure lamp is considerably more complex than for a low-pressure lamp due to the polychromatic nature of the emission. Therefore, numerous factors must be applied to achieve accurate doses. When the average irradiance in the liquid was determined for medium-pressure UV, the irradiance at the center of the sample surface was multiplied by several factors to correct for the variation in the irradiance across the petri dish (petri factor), the attenuation of the beam within the liquid (water factor), the reflection of UV at the liquid surface (reflection factor), and the variation in the sensor sensitivity to wavelength (sensor factor).

The medium-pressure UV dose was determined as described by Bolton (2) and Bukhari et al. (3) and calculated by using software produced by Bolton Photosciences (Ayr, Canada), as described below.

The variation in the UV irradiance across the sample surface was established by determining the petri factor. This factor compensates for the fact that the irradiance is not uniform over the entire surface area of the sample container. To calculate this factor, the average irradiance across the sample surface was determined by measuring specific irradiance every 5 mm along two perpendicular lines that intersect in the middle of the dish. A total of 30 measurements were taken to calculate the average irradiance. The ratio of the average irradiance to the center irradiance determined the petri factor.

To determine the UV absorption by the liquid containing the test organism, a water factor was calculated by using an integrated form of Beer's Law that considers the absorption coefficient and the path length of the liquid. To obtain the UV absorption of the liquid, the absorbance spectrum of the most germicidal wavelengths (ranging from 200 to 300 nm) were determined using a 1-cm quartz cell in a UV spectrophotometer (8453 UV-visible spectrophotometer; Hewlett-Packard, Mississauga, Canada). Both the unweighted average water factor and the weighted average germicidal water factor were determined for the medium-pressure lamp.

Due to the fact that polychromatic medium-pressure lamps do not emit equally at each wavelength, the meter reading does not give an accurate irradiance because it is calibrated at 254 nm. Therefore, a factor to correct for the sensor was applied by using the known spectral output of the lamp. This factor (1.206) was provided by the manufacturer. Also, a constant reflection factor of 0.975 was applied to compensate for the reflection off the liquid surface.

Therefore, to determine the true incident irradiation across the surface of the sample, the irradiance at the center of the petri dish was multiplied by the petri factor and the sensor factor. This value was then multiplied by the reflection factor and the water factor to give the average irradiance through the water (milliwatts per square centimeter). This irradiance value was then multiplied by the exposure time (seconds) to obtain a medium-pressure UV dose (millijoules per square centimeter). Medium-pressure UV doses are expressed as weighted and unweighted values in millijoules per square centimeter (conversion factor $mJ/cm^2 \times 10 = J/m^2$).

Low-pressure UV dose determination. For low-pressure UV lamps, the irradiance can be taken directly from the radiometer because it is calibrated for the emittance wavelength of 254 nm. To accurately determine the low-pressure UV irradiance, a petri factor, reflection factor, and water factor were applied. The water factor for low-pressure lamps was determined by measuring its absorbance at 254 nm. The petri factor and reflection factor were determined as described above for medium-pressure lamps.

Microorganism. *Escherichia coli* (ATCC 11229; American Type Culture Collection, Manassas, Va.) was grown under optimal conditions in nutrient broth (Sigma-Aldrich Canada Ltd., Oakville, Canada) at 37°C in a water bath (Gyrotory water bath shaker, model G76; New Brunswick Scientific, Edison, N.J.) to ensure sufficient cell density. A 20- to 22-h culture in stationary phase was used for experimental purposes to more closely mimic environmental conditions. The suspension was centrifuged (Sorvall FA-Micro; DuPont Canada, Mississauga, Canada) at $350 \times g$ for 8 min, and the supernatant was aseptically drawn off. The pellet was resuspended in 0.01 M phosphate-buffered saline to obtain an *E. coli* concentration of approximately 10^8 cells/ml. The sample was vortexed (Fisher Genie 2; VWR Canada, Mississauga, Canada), and 5 ml was added directly into a 50-mm plastic petri dish (Courtesy Med/Tek, Buffalo Grove, Ill.). Prior to irradiation, a portion of the *E. coli* suspension was removed and serially diluted to determine the initial cell concentration.

Due to sample volume limitations and sampling time constraints, replication was difficult to establish within each experiment. Therefore, to compensate for this, a minimum of two experiments were performed for each irradiation dose (Table 1) and each dilution was plated in triplicate as described below. Data from representative experiments are shown, with standard deviations.

Sample irradiation. The remaining *E. coli* suspension in the petri dish was placed on a stir plate (model PC-161; Corning Incorporated, Kennebunk, Maine) under the collimating tube of the UV unit, where the suspension was thoroughly mixed for 2 min with the aid of a magnetic stir bar (1 by 0.2 cm). With the lid removed and with constant stirring, the sample was exposed to UV radiation for selected periods to yield the desired UV dose. All samples were exposed at room temperature (20 to 22°C). After irradiation, the petri dish was covered with foil to prevent further light penetration.

Immediately following UV exposure, the entire sample volume was collected and placed in a sterile test tube covered with foil. A portion of the irradiated sample was removed, serially diluted, and plated in triplicate on nutrient agar (Sigma-Aldrich Canada Ltd.) to determine the initial organism levels following exposure. The plates were incubated at 37°C for 24 h. All *E. coli* samples were processed by the standard plate count technique (5).

The remaining UV-irradiated sample was separated and transferred into two separate plastic petri dishes (Phoenix Biomedical Products Inc., Mississauga, Canada). These samples were kept at 37°C in a controlled environment incubator (Innova 4230 refrigerated incubator shaker; New Brunswick Scientific) equipped with five 15-W fluorescent grow lamps (Agro-Lite, 46 cm; Philips Lighting Co., Somerset, N.J.). The intensity of the lights at the sample surface was approximately 16,900 lx (model LI-189 light meter with quantum sensor; LI-COR Bioscience, Lincoln, Nebr.). The samples were placed 4 cm below three overhanging lamps. Two other lamps were placed on either side of the dishes. One of the two petri dishes was exposed to light to examine photorepair, and one was covered with foil to allow dark repair. Both samples were continuously mixed on an orbital shaker inside the incubator. A sample was aseptically removed from each dish periodically for up to 4 h following the start of incubation and plated as described above, for enumeration. All samples used to investigate dark repair were diluted in foil-covered tubes to ensure no light exposure.

RESULTS

Currently, there is no standard type or intensity of photoreactivating light recommended for use in reactivation studies. Therefore, a preliminary study was conducted to confirm the ability of the test *E. coli* organisms to carry out photorepair following low-pressure UV exposure. Suspensions of *E. coli* were exposed to low-pressure UV and then to a series of lamps to observe the different levels of photorepair. Photoreactivation was not observed until three 15-W grow lamps were used. A total of five fluorescent grow lamps, as documented by Sommer et al. (23), were used for all photoreactivation trials during this study.

Once conditions for photoreactivation were confirmed, experiments comparing medium- and low-pressure UV inactivation and repair were begun. To determine the log reduction of *E. coli* following UV exposure, the difference in the log of the initial concentration of *E. coli* and the log of the concentration immediately following UV exposure was determined. The average log initial inactivation of *E. coli* immediately following both low- and medium-pressure UV irradiation at 5, 8, and 10 mJ/cm^2 is presented in Table 1.

Because not all wavelengths emitted by medium-pressure lamps are equally effective in the germicidal range (200 to 300 nm) (Fig. 1), the contributions of each wavelength can be "weighted" by the absorption spectrum of DNA, based on the absorbance being 1 at 254 nm (17, 2). The dose determination in this study differs from that of Bukhari et al. (3) in that the medium-pressure UV doses are expressed as both unweighted and weighted (germicidal) medium-pressure UV doses. Weighting medium-pressure doses makes comparisons with data from low-pressure UV doses possible (2). The unweighted UV dose does not weight any of the wavelengths differently and is commonly expressed by other researchers (e.g., see references 3 and 20). The differences between weighted and unweighted UV doses can be seen in preliminary results tables. Throughout this study, only weighted doses are discussed.

When inactivation levels from the same dose of low-pressure and weighted medium-pressure UV are compared, the levels of inactivation should be similar (2). As shown in Table 1, similarities in log inactivation between medium- and low-pressure UV inactivation were observed at doses of 8 and 10 mJ/cm^2 but not at 5 mJ/cm^2. The average log inactivation at 8 mJ/cm^2 was 4.2 and 5.0 under low- and medium-pressure UV, respectively, and that at 10 mJ/cm^2 was 5.0 and 5.2 under low- and medium-pressure UV, respectively. At 5 mJ/cm^2 there was a measurable difference in inactivation following exposure to low- and medium-pressure UV; average log inactivation was 1.6 under low-pressure UV but much higher, 4.9, under medium-pressure irradiation.

A comparison of light and dark repair over time following low- and medium-pressure UV exposure can be observed in Fig. 2. Following exposure to photoreactivating light, all samples exposed to 5, 8, and 10 mJ of low-pressure UV irradiation/cm^2 showed levels of photorepair. Each low-pressure-irradiated sample showed an immediate increase in repair following exposure to photoreactivating light, whereas all samples incubated in the dark showed limited or no repair. Maximum photorepair occurred at 2 h following a low-pressure dose of 5 mJ/cm^2 and at 3 h for low-pressure doses of 8 and 10 mJ/cm^2. However, medium-pressure-irradiated samples at the same doses showed limited or no repair with up to 4 h of incubation in photoreactivating light or dark conditions.

Figure 3 compares the initial *E. coli* concentration (pre-UV) and initial inactivation concentration (post-UV), with light and dark repair levels at the maximum repair time of 180 min following a dose of 10 mJ/cm^2 from low- and medium-pressure UV irradiation. The data in Fig. 3 are averages from two experiments following low-pressure UV and two experiments following medium-pressure UV exposure.

In an effort to further establish whether repair could take place following medium-pressure UV exposure, the dose was lowered to 3 mJ/cm^2. After incubation in photoreactivating light, a slightly higher level of repair was observed than with other medium-pressure doses (Fig. 4). Unlike the low-pressure-irradiated samples, repair was not observed immediately following exposure to photoreactivating light and was not detectable until after 60 min of exposure. A maximum effective repair (calculation shown below) was shown to be 0.6 log following 240 min of light exposure. No detectable repair was observed following sample incubation in the dark.

From the data presented in Tables 2 and 3, an "effective" log repair value was determined for light and dark conditions at doses of 5, 8, and 10 mJ/cm^2. Effective log repair was calculated as the difference between the log CFU/ml following repair conditions and log CFU/ml immediately following UV exposure.

The most measurable difference in repair potential between low- and medium-pressure UV was observed at doses of 10 and 8 mJ/cm^2. Following low-pressure irradiation at a dose of 10 mJ/cm^2, an effective log repair of 2.8 was observed under light conditions, while no photorepair was measurable following medium-pressure UV at the same dose (Table 2 and Fig. 3). Exposure of samples to light following UV irradiation at 8 mJ/cm^2 showed an effective

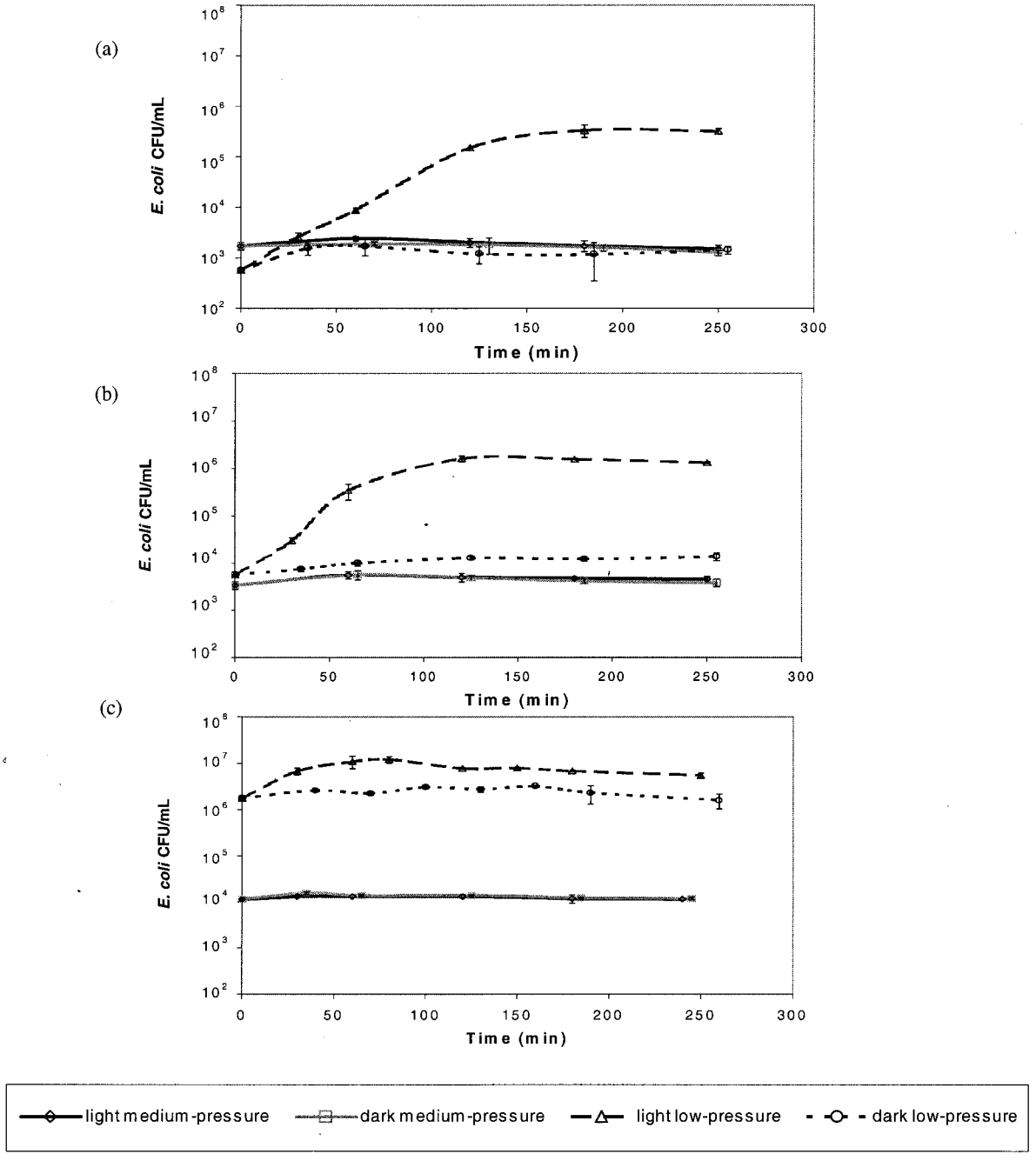

FIG. 2. Photorepair and dark repair potential of *E. coli* following low- and medium-pressure UV irradiation at doses of 10 (a), 8 (b), and 5 (c) mJ/cm^2.

log repair of 2.6 following low-pressure irradiation and 0.1 after medium-pressure irradiation (Table 2). Following a low-pressure dose of 5 mJ/cm^2, levels of *E. coli* repair under light incubation showed an effective log repair of 0.7. Medium-pressure-irradiated samples at the same dose showed low levels of effective log repair in light of 0.1 (Table 2). Sample incubation in the dark following both low- and medium-pressure UV irradiation showed limited or no observable effective dark repair (Table 3).

DISCUSSION

E. coli was selected for this study because it is commonly used as a biological indicator of disinfection efficiency in water systems. Its repair processes following exposure to low-pressure UV are well known and have been studied in extensive detail. This strain was specifically chosen because it is known to undergo photorepair following low-pressure UV exposure up to a dose of 28 mJ/cm^2 (12).

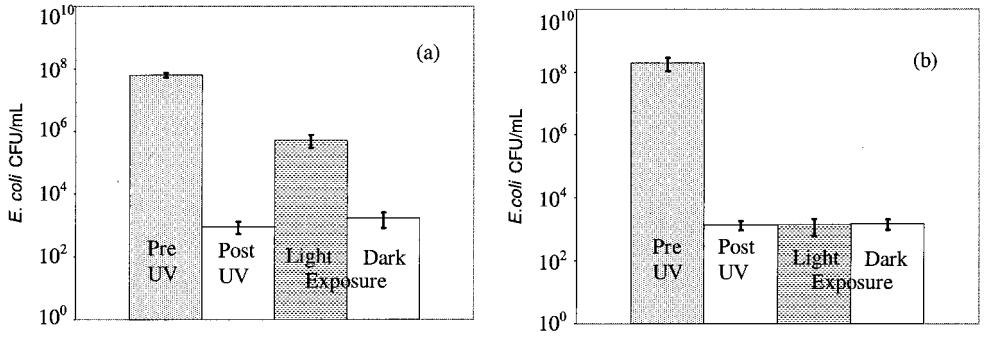

FIG. 3. Irradiation of *E. coli* at 10 mJ/cm^2 from low-pressure (a) and medium-pressure (b) UV sources showing average concentrations prior to irradiation (pre UV), following irradiation (post UV), and following incubation under photoreactivating light and dark conditions at an optimal time of 180 min. Averages and standard deviations are based on two separate experiments, each using three plates per appropriate dilution ($n = 6$).

Given that the photoreactivating enzyme photolyase requires specific wavelengths (300 to 500 nm) and certain intensities of light to carry out repair (7), a preliminary study was preformed to determine the appropriate light source for photoreactivation. This preliminary investigation determined that *E. coli* could carry out photorepair only following exposure to a specific number of fluorescent grow lamps. A lack of a standardized procedure for quantifying photoreactivation makes comparisons with other studies difficult. This preliminary study stresses the importance of positive control organisms in reactivation studies and advises caution in interpreting previous reactivation studies that did not use positive reactivation controls.

The results from this study clearly support previous research indicating photorepair of *E. coli* following exposure to low-pressure UV irradiation (11, 12, 22, 23). Following exposure to low-pressure UV irradiation, *E. coli* repair under photoreactivating light increased rapidly, reaching maximum levels at about 2 to 3 h before leveling off. A lag in repair time was detected at higher doses, as the time needed for repair increased with increase in UV dose (Fig. 2). This is due to the fact that higher UV doses induce greater damage to the DNA. Therefore, it takes longer to repair the damage, since there are only approximately 20 photolyase enzymes in each *E. coli* organism (7, 8) and each enzyme can repair only approximately 5 dimers per min (7, 9).

Although photorepair was observed after each dose of low-pressure irradiation, the levels of repair never reached the initial concentration of *E. coli* prior to UV exposure. Therefore, complete repair did not occur, which indicates that irreversible damage occurred to cells. All samples incubated under dark conditions showed much lower levels of repair (Fig. 2), as previously reported in the literature (23)

The increased use of medium-pressure UV lamps in water treatment has prompted the evaluation of its ability to inactivate microorganisms compared to low-pressure UV systems. DNA has always been regarded as the most important and primary target molecule for UV radiation. Although extensive DNA damage occurs from exposure to emissions from low-pressure UV lamps, it has been suggested that broader wavelengths emitted by medium-pressure UV lamps may cause additional damage to organisms, leading to subsequently higher levels of inactivation (16, 19). Studies have shown that wavelengths other than those emitted by low-pressure lamps can induce DNA damage to different extents (e.g., see references 10 and 14). In addition to DNA, other biological molecules might also be subject to the effects of medium-pressure wavelengths. UV wavelengths emitted by medium-pressure lamps include the UV-A (320 to 400 nm), UV-B (290 to 320

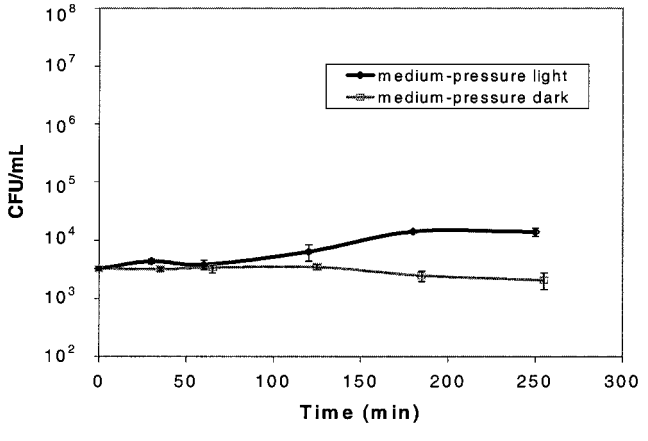

FIG. 4. Photorepair and dark repair potential of *E. coli* following medium-pressure UV irradiation at a dose of 3 mJ/cm^2.

TABLE 2. Average effective log repair of *E. coli* under light incubation conditions

Weighted UV dose (mJ/cm^2)	UV source	Time for maximum repair (min)	Log CFU/ml (avg ± SD) after:		Avg effective log repair[a]
			UV	Exposure to reactivating light	
5	Low	120	6.1 ± 0.12	6.8 ± 0.18	0.7
5	Medium	120	3.8 ± 0.90	3.9 ± 0.71	0.1
8	Low	180	3.6 ± 0.38	6.2 ± 0.03	2.6
8	Medium	180	3.4 ± 0.32	3.5 ± 0.44	0.1
10	Low	180	3.0 ± 0.24	5.7 ± 0.25	2.8
10	Medium	180	3.1 ± 0.17	3.1 ± 0.18	0.0

[a] Calculated as log CFU per milliliter after light exposure − log CFU per milliliter after UV.

TABLE 3. Average effective log repair of *E. coli* under dark incubation conditions

Weighted UV dose (mJ/cm^2)	UV source	Time for maximum repair (min)	Log CFU/ml (avg ± SD) after:		Avg effective log repair[a]
			UV	Exposure to dark	
5	Low	120	6.1 ± 0.12	6.2 ± 0.19	0.1
5	Medium	120	3.8 ± 0.90	3.9 ± 0.81	0.1
8	Low	180	3.6 ± 0.38	3.9 ± 0.28	0.4
8	Medium	180	3.4 ± 0.32	3.4 ± 0.52	0.0
10	Low	180	3.0 ± 0.24	3.2 ± 0.18	0.3
10	Medium	180	3.1 ± 0.17	3.2 ± 0.13	0.0

[a] Calculated as CFU per milliliter after dark exposure − CFU per milliliter after UV.

nm), and UV-C (190 to 290 nm) ranges. Wavelengths in the UV-A range can affect membranes and membrane functions, and wavelengths in the UV-B and UV-C ranges have shown to be absorbed by proteins (15, 10). Recent studies in drinking water treatment situations have shown comparable levels of inactivation from low- and medium-pressure UV lamps (e.g., see references 6 and 13). In the present study, irradiation at 8 and 10 mJ/cm^2 from low-pressure and weighted medium-pressure UV resulted in comparable levels of inactivation, but at doses of 5 mJ/cm^2 this degree of similarity was not observed (Table 1). This lower dose demonstrated a much higher degree of inactivation following medium-pressure UV irradiation.

Most studies to date evaluating medium-pressure UV efficacy in water treatment have examined the levels of inactivation but have not taken into account the levels of repair that may follow (3, 4, 6, 13, 20). To date no studies have evaluated repair following exposure to UV radiation from medium-pressure lamps used in water treatment. This study clearly shows that there is a substantial difference between photorepair following low- and medium-pressure UV irradiation. Although high levels of photorepair were observed following low-pressure irradiation, samples exposed to medium-pressure irradiation at the same doses showed limited or no photorepair.

To determine if photorepair could be observed following medium-pressure UV exposure, the dose was lowered from 5 to 3 mJ/cm^2. At this lower dose, a slightly higher level of *E. coli* photoreactivation was observed (Fig. 3). Although repair was measurable, the levels were substantially lower and occurred over a longer period than those following low-pressure UV irradiation at the doses studied. This finding demonstrates that there is a threshold below which photorepair is possible after medium-pressure UV applications.

While the reasons for the differences in repair were not directly investigated in this study, it can be hypothesized that damage to some part of the repair process may account for the lack of repair following exposure to medium-pressure UV radiation. Other researchers have previously reported inhibition of repair from specific wavelengths of UV (25, 26, 27). For example, inhibition has been observed at very high doses of UV-A (27) and through synergistic effects between two UV-A wavelengths (26). Inhibition of repair might reflect the specific ability of UV-A to induce irreversible physiological changes, including metabolic inhibition (25). Based on the results from this study, there may be synergistic effects between a number of wavelengths emitted by medium-pressure lamps that do not occur with low-pressure lamps.

Another possible explanation for repair inhibition might be that the repair enzymes themselves are damaged. At UV wavelengths below 230 nm (in the UV-C range) there is a very high UV absorption by proteins. Absorption by protein at these wavelengths has been shown to be equal to that by DNA at 260 nm (10). Although UV absorption by proteins is generally considered of little consequence to cells (15), any damage to repair molecules would be critical due to the fact that there are so few repair enzymes present in the cell (8).

In summary, this study demonstrates the difference in the photoreactivation ability of a nonpathogenic strain of *E. coli* following low- and medium-pressure UV irradiation. The results of this study show that polychromatic medium-pressure UV radiation may offer an advantage over monochromatic low-pressure UV radiation in lower-dose water treatment applications. Medium-pressure UV may provide better protection against photoreactivation if UV treatment occurs prior to process units in which water is exposed to light for even short lengths of time (30 to 180 min). Using low-pressure UV in this type of situation should be avoided, since repair occurs rapidly following exposure to light.

It is recommended that further studies be carried out with medium-pressure UV to determine which wavelengths cause additional damage and where the damage is induced. Studies to investigate the results of this research on other microorganisms are in progress. In addition, as a result of the findings in this paper, further research involving real treatment plant waters is warranted.

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