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Solar disinfection (SODIS): simulation of solar radiation for global assessment and application for point-of-use water treatment in Haiti

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Abstract

Haiti and other developing countries do not have sufficient meteorological data to evaluate if they meet the solar disinfection (SODIS) threshold of 3–5 h of solar radiation above 500 W/m^2, which is required for adequate microbial inactivation in drinking water. We have developed a mathematical model based on satellite-derived daily total energies to simulate monthly mean, minimum, and maximum 5-h averaged peak solar radiation intensities. This model can be used to assess if SODIS technology would be applicable anywhere in the world. Field measurements were made in Haiti during January 2001 to evaluate the model and test SODIS efficacy as a point-of-use treatment option. Using the total energy from a measured solar radiation intensity profile, the model recreated the intensity profile with 99% agreement. NASA satellite data were then used to simulate the mean, minimum, and maximum 5-h averaged peak intensities for Haiti in January, which were within 98.5%, 62.5%, and 86.0% agreement with the measured values, respectively. Most of the discrepancy was attributed to the heterogeneous nature of Haiti's terrain and the spatial resolution of the NASA data. Additional model simulations suggest that SODIS should be effective year-round in Haiti. Actual SODIS efficacy in January was tested by the inactivation of total coliform, *E. coli*, and H_2S-producing bacteria. Exposure period proved critical. One-day exposure achieved complete bacterial inactivation 52% of the time, while a 2-day exposure period achieved complete microbial inactivation 100% of the time. A practical way of providing people with cold water every morning that has undergone a 2-day exposure would be to rotate three groups of bottles every morning, so two groups are out in the sun and one is being used for consumption. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Solar disinfection; Solar simulation; Water treatment

1. Introduction

Many developing countries cannot afford conventional means of water treatment. In Haiti, only 45% of the rural population have access to safe water [1] causing waterborne disease to be widespread. Between 1987 and 1994, 47.7% of 6–11-month-old infants had diarrhea, which is the leading cause of illness and death in children less than 5 years of age [2]. If correctly managed, Haiti has ample water—but an economical and easy way to destroy waterborne pathogens is needed. Solar disinfection (SODIS) is thought to be a viable water treatment option because of the minimal investment cost of a plastic bottle and simple disinfection procedure. This process produces pathogen-free water by filling 1–2 L polyethylene terephtalate (PET) bottles and exposing them to sunlight. To achieve microbial inactivation, a solar radiation threshold must be met. In this project, a mathematical model is presented to simulate solar radiation intensity profiles to assess if SODIS would be applicable for a given region. Field measurements

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were made in Haiti to validate the model and test SODIS efficacy as a point-of-use treatment option through microbial analysis.

1.1. Solar disinfection

To ensure adequate microbial inactivation, 3–5 h of solar radiation above 500 W/m^2 should be available [3]. The sun's UV-A, red, and infrared radiation can inactivate pathogens via three mechanisms. First, UV-A absorbance by DNA can cause adjacent thymine bases to covalently bond to form thymine dimers, which can prematurely terminate DNA replication [4–7]. Additionally, incorrect repair of thymine dimers may also cause mutations [8]. Second, natural dissolved organic matter absorbs UV to induce photochemical reactions [9] that create highly reactive species such as superoxides (O_2^-), hydrogen peroxides (H_2O_2), and hydroxyl radicals ($OH^\bullet$) [10,11]. These can damage microorganisms by oxidizing cellular components [6,7,10]. Third, water strongly absorbs red and infrared light creating heat. Temperatures greater than the maximum growth value cause denaturation, which impedes protein function and may kill the organism [12]. Synergistic UV and thermal effects are observed at a water temperature of 45°C [6]. Compared to lower water temperatures, only one-third of the UV-A fluence was required to inactivate *E. coli* at 50°C [13]. Inactivation of a wide range of microbiota by the aforementioned SODIS mechanisms has been well documented in the literature [4,13] and there is currently active research to investigate additional critical pathogens such as *Giardia* [14].

1.2. Possible limitations of SODIS effectiveness

Ambient air temperature, topography and microclimate, and water turbidity can influence SODIS efficacy. Ambient air temperature enhances SODIS if above 20°C [14]. Topographical effects can impede SODIS effectiveness by creating locally adverse microclimates with insufficient solar radiation and/or temperature. Mountainous areas, for example, are subject to increased cloud cover due to orographic lifting and cooler temperatures compared to lower elevations. Finally, water turbidity may interfere with SODIS by limiting the amount of light penetration. For effective SODIS, turbidity should be less than 30 nephelometric turbidity units (NTU) [15].

Haiti has a tropical climate with the countrywide average temperature ranging from 24°C in the winter to 28°C in the summer. However, approximately 63% of all land in Haiti has slopes greater than 20% and only 29% has slopes of less than 10% [16]. The mountainous terrain affects both solar influx and temperature. For example, the village of Kenscoff at an elevation of 1432 m has an average temperature of 16°C, while Port-au-Prince, at sea level, has an average temperature of 26°C. These observations suggest that SODIS could have limited effectiveness in the mountainous regions of Haiti. Lantagne [17] sampled raw water in several locations throughout Haiti to find that they all had minimal turbidity well below 30 NTU.

2. Simulation of solar radiation for SODIS assessment

The most important parameter driving SODIS is solar radiation intensity. For a geographical area to be suitable for SODIS, it must receive 3–5 h of solar radiation above 500 W/m^2 [3]. However, many areas of the world that could benefit from SODIS are developing countries and do not have adequate meteorological data to assess if SODIS is an appropriate technology. To overcome this lack of data, a method of simulating daily solar radiation intensity profiles anywhere in the world is presented. The peak 5 h around noon of these profiles can be averaged and then compared to the solar radiation disinfection threshold to assess potential SODIS application.

2.1. Mathematical development of solar radiation simulation

We simulated daily solar radiation intensity profiles based on the 10-year mean, minimum, and maximum amount of total daily radiation received for a representative day of each month provided by NASA Langley Atmospheric Sciences Data Center's web site [18]. These data have a spatial resolution of 1° latitude and longitude for the entire world. These profiles were then used to calculate the mean, minimum, and maximum 5-h averaged peak intensities to get a first approximation of whether SODIS would be applicable during any given month. Our general approach is to calculate the day length based on location and time of the year, which is a function of the earth's declination angle and sunrise angle. Next, the sun's hour angle is obtained. This combined information is used to determine what fraction of the total radiation is received at a given hour, ultimately generating a daily solar radiation profile.

The declination angle, ω_d (°), is the angle at solar noon between the sun and the equator, referenced as north positive. It can be approximated for a specific Julian day from the equation given by Cooper [19]

$$\omega_d = 23.45 \sin\left(\frac{360(284 + n_{jday})}{365}\right), \quad (1)$$

where n_{jday} is the Julian day (number of days after January 1). For practical purposes, Duffie and Beckman

Table 1
Recommended average day and declination angle for each month [20][a]

Month	Date	Julian day[b]	Declination, ω_d (°)
January	17	17	−20.9
February	16	47	−13.0
March	16	75	−2.4
April	15	105	9.4
May	15	135	18.8
June	11	162	23.1
July	17	198	21.2
August	16	228	13.5
September	15	258	2.2
October	15	288	−9.6
November	14	318	−18.9
December	10	334	−23.0

[a] Values taken directly from [21].
[b] Values do not account for leap year; correct by adding 1 to months from March onward. Declination will also slightly change.

[20] provide a table with declination angles that are representative of each month (Table 1).

The hour-angle, ω_t (°), is the angular displacement of the sun east or west of the local meridian due to rotation of the earth at 15°/h. The hour-angle can be calculated from [21]

$$\omega_t = (t - 12)15, \tag{2}$$

where t is the time from midnight (h).

The sunset or sunrise hour-angle, ω_s (°), is the hour-angle when the sun's center reaches the horizon and can be computed if the location's latitude, L (°), and current declination, ω_d, are known [22]

$$\omega_s = \cos^{-1}(-\tan(L)\tan(\omega_d)). \tag{3}$$

Eq. (4) gives the ratio, r_t, of hourly to daily radiation at any given hour [20]:

$$r_t = \frac{\pi}{24}(a + b\cos\omega_t)\frac{\cos\omega_t - \cos\omega_s}{\sin\omega_s - (\pi\omega_s/180)\cos\omega_s},$$
$$a = 0.409 + 0.5016\sin(\omega_s - 60),$$
$$b = 0.6609 - 0.4767\sin(\omega_s - 60). \tag{4}$$

With this ratio known, and obtaining the total daily solar radiation, I_{ad} (Wh/m^2), from a source such as NASA, the average hourly intensity value, I_{ah} (W/m^2), can be calculated

$$I_{ah} = r_t I_{ad}. \tag{5}$$

To generate a daily intensity profile, ω_s is calculated from Eq. (2) or obtained from Table 1. Next, ω_t is calculated at different temporal intervals roughly covering sunrise to sunset. For each value of ω_t, a corresponding ratio of hourly to daily radiation is calculated from Eq. (4). These ratios are then substituted into Eq. (5) to produce an intensity profile and the peak 5 hours are averaged for comparison to the SODIS threshold.

3. Materials and methods

3.1. Solar radiation measurements and model simulations

Field measurements were made on January 12 and 13 in Dumay, and from January 15 to 21, 2001 in Santo, Haiti, both suburbs of Port-au-Prince. Solar radiation intensity was measured at hourly intervals with a Kipp and Zonen Solrad kit. The average measured solar radiation of the sunny days was used to construct an intensity profile, which was then integrated to obtain the average total amount of daily energy received. The model then used this daily total amount of energy, along with the corresponding declination angle and latitude, to recreate the measured solar radiation profile for validation. Next, the model was used to simulate solar radiation intensity for Haiti throughout the year. Haiti lies within seven 1°-latitude-by-longitude cells in the NASA solar radiation database. For each cell, the NASA values of mean, minimum, and maximum daily total radiation were used to generate intensity profiles for each month of the year. From these results, a general solar radiation intensity envelope of the mean, minimum, and maximum 5-h averaged peak intensities was obtained from the spatial average across Haiti. These monthly values were compared to the SODIS threshold. Finally, to evaluate how well the model predicted Haitian solar radiation intensity using the NASA data for January 2001, the simulations were compared to the measurements.

3.2. SODIS evaluation in Haiti

Nine 1.5 L PET bottles were collected from a home, local refuse, and a local store. Black paint was applied to the elongated bottom half of each bottle to enhance thermal effects. During January 12 and 13, six bottles were used. Three bottles were placed in the dark to serve as controls and three were left out in the sun for 1 day. In addition, samples exposed to solar radiation from the first day were kept for the duration of the study to test for possible bacterial regrowth. From January 16 to 21, nine bottles were used to assess the effects of both 1- and 2-day exposure. This bottle arrangement was divided into three groups with three bottles per group: 1-day, 2-day$_1$, and 2-day$_2$. The two 2-day groups were exposed in an overlapping staggered arrangement, which allowed for the effects of 2-day exposure to be measured every day. Water was collected from local spring wells, tap water, and an irrigation stream early in the morning using the SODIS bottles. Bottles were initially filled about two-thirds and shaken vigorously for 30 s to provide aeration for photo-oxidative disinfection. They were then completely filled and placed on a rooftop where bottle water temperature measurements were made with Enviro-Safe® thermometers in addition to solar radiation intensity. Raw water samples were taken for turbidity, using a Hach Pocket Turbidimeter, and microbial analysis. Total coliform and *E. coli* were tested for using Hach's presence–absence broth while H_2S-producing bacteria was evaluated using Hach's PathoScreen™. Microbial tests were run in triplicate with blanks both before and after setting the bottles out in the sun.

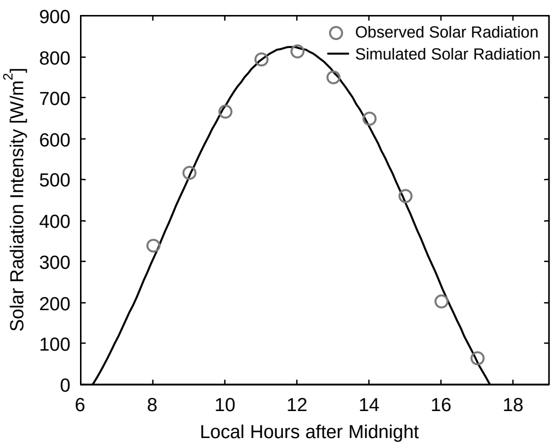

Fig. 1. Model validation of measured versus recreated solar radiation intensity profile.

4. Results

4.1. Solar radiation measurements and model simulations

The model accuracy is demonstrated by over 99% agreement between the measured and mathematically recreated solar radiation intensity profile (Fig. 1). The validated model was used to simulate solar radiation intensities for Haiti based on the NASA data. The simulated mean, minimum, and maximum Haitian 5-h averaged peak intensities are above the disinfection threshold all year (Fig. 2).

To evaluate how well the model predicted Haitian solar radiation intensity using the total daily radiation values from NASA, the simulations were compared to the measurements. The simulated mean, minimum, and maximum 5-h averaged peak intensities were within 98.5%, 62.5%, and 86.0% agreement with the measured values, respectively. The discrepancy between the simulated and measured minimum and maximum 5-h averaged peak intensities can be explained by the percent agreement between the NASA total daily radiation values used for the simulations and measured total radiation, which are in 62.4% and 88.6% agreement, respectively. This agreement adequately explains

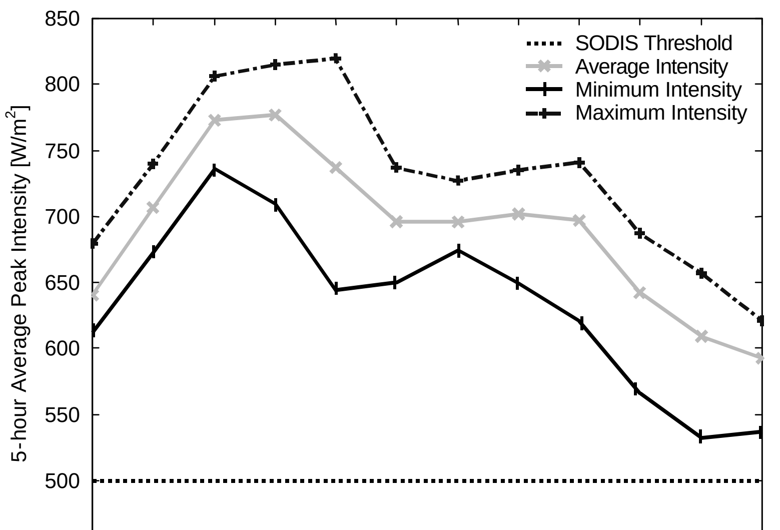

Fig. 2. Yearly 5-h averaged mean, minimum, and maximum intensity profile of Haiti based on NASA Solar Energy Database [18].

the 62.5% and 86.0% agreement between the 5-h averaged peak intensities because the total daily radiation is so intimately related to the daily radiation intensity profile (as shown by Eqs. (4) and (5)). To verify that the disagreement arises from the NASA data and not the model, the measured minimum and maximum total daily radiation values were substituted into the model to produce corresponding 5-h averaged peak intensities with over 99% agreement with the observed minimum and maximum 5-h averaged peak intensities.

4.2. SODIS evaluation in Haiti

Daily solar radiation and bottle water temperature profiles were measured to determine whether Haiti's climate is suitable for SODIS according to the recommended thresholds. The average solar radiation from January 12 through 21, 2001 had a 5-h averaged peak intensity of 651 W/m^2 with a daily total radiation of 4537 Wh/m^2. On average, the bottle water temperature reached the synergistic temperature threshold of 45°C for about 3 h. Seven days were mostly sunny while two were overcast. During the 7 mostly sunny days the 5-h averaged peak intensity was 735 W/m^2, and the total amount of radiation received was 5061 Wh/m^2. The bottle water temperature rose past the synergistic threshold for over 4 h (Fig. 3). However, for the average of the two overcast days, the 5-h averaged peak intensity was below the solar radiation intensity threshold at 457 W/m^2 and the total amount of radiation received was 2958 Wh/m^2. The bottle water temperature never reached the synergistic threshold (data not shown).

All of the water sources tested were very clear with an average turbidity of 1.3 ± 0.6 NTUs. This implies that water clarity would not obstruct microbial inactivation by SODIS. For each type of microbial test performed, the total results for the raw water, 1-day exposure, and 2-day exposure are given by Table 2. The average presence–absence agreement between the three types of microbial tests was 94.6 ± 0.02%, indicating that SODIS was indiscriminant in its effects on the different target organisms. The raw water results from various sources confirm that Haiti has problems with microbial contamination since 97% of the samples tested positive for all indicator organisms. The 1-day exposure period produced varying amounts of inactivation. No microbial inactivation was observed for each of the two overcast days, which had an average 5-h averaged peak intensity of 457 W/m^2 and a bottle water temperature below the synergistic threshold. Approximately 66% complete microbial inactivation was observed on each of 3 days that had an average 5-h averaged peak intensity of 718 W/m^2 and a bottle water temperature above the synergistic threshold for 2 h. Complete microbial inactivation was obtained with a 1-day exposure on 3 days that had an average 5-h averaged peak intensity of 752 W/m^2 and the bottle water temperature above the synergistic threshold for 5 h. These results indicate that it is possible to have complete microbial inactivation with 1-day exposure under the right conditions. However, the 2-day exposure period produced complete

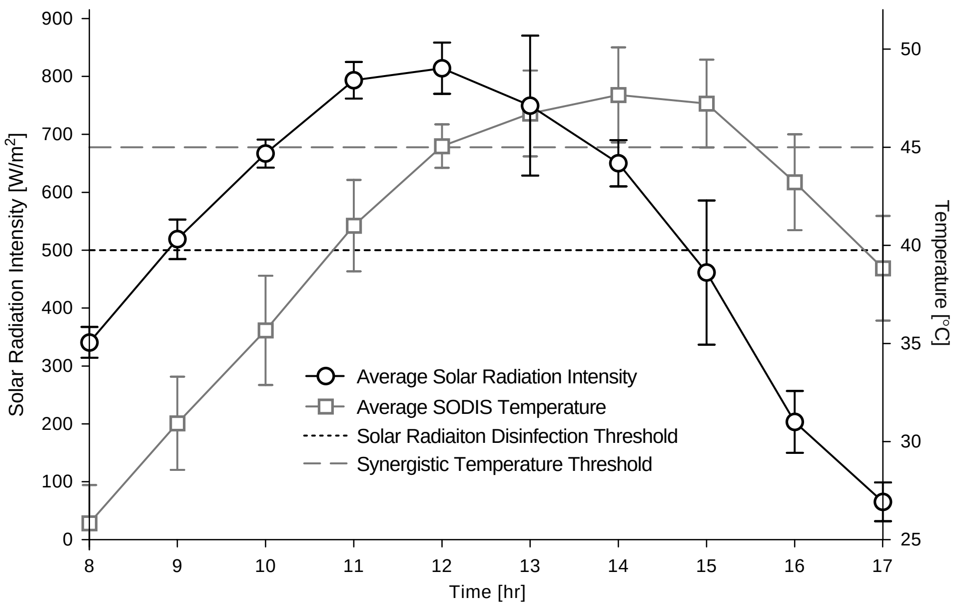

Fig. 3. Average solar radiation and bottle water temperature profile for mostly sunny days ($N = 7$).

Table 2
Total microbial analysis

Target organisms	% (Positive/sampled)[a]		
	Raw water	1-day exposure	2-day exposure
Total coliform[b]	100.0% (24/24)	50.0% (12/24)	0.0% (0/18)
E. coli[b]	91.7% (22/24)	45.8% (11/24)	0.0% (0/18)
H_2S producing[c]	100.0% (24/24)	41.7% (10/24)	0.0% (0/17)
Total	97.2% (70/72)	48.3% (33/72)	0.0% (0/53)

[a] Values in parenthesis are number positive tests out of number of tests performed.
[b] Total coliform and *E. coli* were tested with Hach's presence–absence broth.
[c] H_2S producing bacteria were tested with Hach's PathoScreen™.

microbial inactivation 100% of the time for all conditions experienced including the two non-consecutive overcast days. No bacterial regrowth was observed and all of the dark controls tested positive for all types of organisms, which is consistent with Wegelin et al. [13].

5. Discussion

The mathematical solar radiation model presented in this paper is a valuable tool to obtain a first approximation of SODIS applicability for anywhere in the world throughout the year. One would only need to obtain the location's latitude, declination angle, and total daily radiation values from a source such as NASA. If the solar radiation intensities appear adequate for a location, then physical tests should be conducted to evaluate SODIS. The model proved accurate for predicting a 5-h averaged peak intensity for a corresponding total daily radiation value. Caution should be used when applying the NASA values obtained for the 10-year average of the mean, minimum, and maximum total daily radiation. Their spatial resolution does not capture the presence of microclimates within a degree longitude and latitude, which can cause inaccurate predictions for specific locations. Simulated values would likely be much more accurate for locations in orographically homogeneous regions.

The highly heterogeneous nature of Haiti's climate makes general conclusions difficult to formulate. At higher altitudes, the orographically enhanced cloud cover and the colder temperatures could compromise the effectiveness of SODIS. If the mountainous regions are too cold to realistically incorporate synergistic thermal effects, the bottles should not be painted black but could be placed in solar reflectors. This would have the SODIS process rely solely on optical inactivation, which could be very effective given there is more UV radiation at higher altitudes.

For the areas studied in Haiti, the intense solar radiation and warm climate appear to provide conditions suitable for effective SODIS. This research was conducted during Haiti's winter, implying shorter and colder days compared to most of the year. It would also be important to conduct further SODIS testing around May and November when there is less solar radiation and increased cloudiness due to the rainy season. During these months, the model simulations in Fig. 2 show the 5-h averaged minimum intensity is substantially decreased from the maximum due to enhanced cloud cover on rainy days. However, the 5-h averaged minimum intensity is still above the recommended threshold implying SODIS will still be effective during Haiti's rainy season.

Exposure period to solar radiation proved critical for consistent 100% bacterial inactivation. Solar radiation can be highly variable and the right conditions for 100% inactivation with 1-day exposure were only met half of the time, while a 2-day exposure period achieved complete microbial inactivation every time. Guidelines that differentiate between 1- and 2-day exposure have been given in the literature. Our study suggests it may be more practical to have every bottle exposed for a 2-day duration. A continuous 2-day exposure period would take much of the speculation out of this technology and always achieve more conservative disinfection. To ask a user to gauge how much solar radiation was received on any given day is burdensome and probably prone to errors, which could ultimately cause illness or death. A practical way of providing people every morning with cold water that has undergone a 2-day exposure period can be termed "a SODIS triangle". Essentially, it consists of three groups of bottles that are rotated every morning, so two groups are exposed to the sun and one is being used for consumption. This establishes an indefinite loop where a person goes out in the morning to fill up a group of bottles and returns the same morning with a group of bottles that have undergone 2 days of SODIS treatment. This has the added advantage that the bottles have been allowed to cool over night. An important potential limitation of setting up a SODIS triangle could be an insufficient quantity of available bottles. If the number of bottles is scarce, then continuous 2-day exposure would not be possible and the users should follow the exposure guidelines recommended by Wegelin and Sommer [23], which basically recommend exposure of 5 h on a sunny day and 2 consecutive days when the sky is overcast. Even though complete microbial inactivation was not always achieved for a 1-day sunny exposure period in our study, the bacterial numbers may have been reduced into the low risk category of 1–10 faecal coliform or E. *coli* per 100 ml [24]. At worst, a 1-day exposure period can only improve the water quality.

6. Conclusions

1. The mathematical technique for simulating solar radiation intensity profiles presented in this paper should provide a means of initially assessing SODIS applicability for a given region anywhere in the world. Caution should be used if there is significant topographical heterogeneity within the spatial resolution of the total daily radiation data.
2. The solar radiation intensity simulations based on the NASA data imply that SODIS should be effective year-round in Haiti. However, higher altitudes may limit SODIS efficacy due to orographic enhanced cloud cover and cooler temperatures.
3. A 2-day exposure period was observed to produce complete microbial inactivation every time judging from three different indicator organism tests. Thus, if an adequate number of bottles is or could be made available, rotating three groups of bottles every morning would allow the water used for consumption to have undergone the essentially risk-free 2-day exposure period.
4. Overall, the results are encouraging and it is strongly recommended that SODIS be further investigated for Haiti. Ultimately, this point-of-use treatment option could provide a safe source of water at the cost of a plastic bottle.

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