CHAPTER 7

Water Disinfection

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RISK OF WATER-BORNE INFECTION

Water disinfection is an essential component of the prevention strategy for enteric infections. In developing countries, surface water may be highly contaminated with human waste. The World Health Organization (WHO) reports that 780 million people still lack access to an improved drinking water supply, and 2.4 billion people lack access to improved sanitation. This lack of safe drinking water, sanitation, and hygiene accounts for an estimated 2 million deaths in children under 5 years of age, nearly 90% of diarrhea in all ages, and as much as 4% of all deaths globally. Urban tap water may become contaminated from aged, overwhelmed sanitation plants and deteriorating water distribution systems. Bottled water is a convenient solution, but in some places, it may not be superior to the tap water. Moreover, the plastic bottles create a huge ecological problem, since most developing countries do not recycle plastic bottles. Even in developed countries with low rates of diarrhea illness, wilderness travelers who rely on surface water for drinking and residents in areas affected by a disaster should take steps to ensure microbiologic quality. In the United States, there have been water-borne outbreaks of *Giardia*, *Shigella*, *Campylobacter*, *Escherichia coli* O157:H7, norovirus, and *Cryptosporidium*, some from untreated surface water and others from community water systems.

The list of potential water-borne pathogens is extensive and includes bacteria, viruses, protozoa, and parasitic helminths. More than 120 different enteric viruses alone can be transmitted by fecal-contaminated water. Most of the organisms that can cause traveler's diarrhea can be water-borne; however, the majority of travelers' intestinal infections are probably transmitted by food. Cholera and *Salmonella typhosa* are well known to cause extensive water-borne outbreaks. Water is considered the main route of transmission for hepatitis E and is one of the potential routes for hepatitis A and salmonellosis.

Risk of illness depends on the number of organisms ingested, which in turn depends on the degree of water contamination from human and animal waste, immune status and individual susceptibility, and virulence of the organism (**Table 7.1**). Microorganisms with small infectious dose can even cause illness through recreational water exposure such as swimming as a result of inadvertent water ingestion. Organisms that have been implicated recently in outbreaks resulting from recreational water exposure (including several in the United States) include *Giardia*, *Cryptosporidium*, *Shigella*, *E. coli* O157:H7, norovirus, and gastroenteritis from other unidentified enteric viruses.

Persistence of microorganisms in water facilitates the potential for transmission; cold water greatly prolongs survival (**Table 7.2**). Some enteric bacteria can also survive and even multiply in organic-rich tropical waters. There is a common misconception that streams "purify" themselves over a short distance. Natural die-off of organisms and the disinfection effects of ultraviolet light decrease the number of viable microorganisms, but these are not reliable enough to ensure potable water in a stream. Microorganisms also clump to particles and settle to the bottom in still water but are easily stirred up and redistributed. This does suggest that when taking surface water from a lake, one should try to obtain the water from

TABLE 7.1 Minimal Infectious Dose

Organism	Minimal Infectious Dose
Salmonella	10^5
Vibrio cholerae	10^3
Cryptosporidium	30
Giardia	10
Enteric viruses	1-10

TABLE 7.2 Survival of Microorganisms in Water

Organism	Survival
Vibrio cholerae	4-5 weeks in cold water
Giardia lamblia	2-3 months at 5-10° C
	10-28 days at 15° C
Cryptosporidium	12 months in cold water
Enteric viruses	6-10 days at 15-25° C
	30 days at 4° C
Norovirus	61 days in ground water at 25° C
Hepatitis A	12 weeks in temperate water
	6-12 months in cold water
Salmonella, *Shigella*	Half-life 16-24 h in temperate stream

underneath the surface, where particles float from surface tension, while not disturbing bottom sediment.

Many organisms, such as *Giardia*, *Salmonella*, and *Cryptosporidium*, can be zoonotic and have animal reservoirs, but most surface water contamination probably comes from human fecal contamination. It is important to properly dispose of personal waste. Wilderness hikers and backpackers should bury feces 6-10 inches in the soil, at least 100 feet from any water source and any natural drainage.

Accurate information concerning water quality is difficult to obtain in any country. Where sanitation systems are lacking, which is still the case in many rural areas of developing countries, all surface water should be considered highly contaminated, and tap water should be highly suspect. Any water that receives partially treated wastes, including in North America, is likely to contain pathogenic microorganisms, especially protozoa. Unfortunately, natural metals such as arsenic or chemical and nuclear wastes from industrial dumping and agricultural and mining run-off may be unrecognized or unacknowledged pollutants of water supplies. Expatriates and long-term travelers staying in a given area should try to obtain information from the Consulate or other expatriates about the safety of the local municipal water supplies.

FIELD TECHNIQUES FOR WATER TREATMENT

Fortunately, there are reliable field methods for ensuring the microbiologic safety of drinking water. A large body of recent research confirms the beneficial effect of all standard techniques at the household or individual point of use level to improve water quality and reduce diarrheal illness (**Table 7.3**). The main methods to eliminate microorganisms from water are heat, filtration, chemical disinfection, and ultraviolet treatment. Other techniques may be needed to improve the esthetic quality of the water or to remove chemical contamination. Each technique is discussed along with its respective advantages and disadvantages. Understanding the principles of water disinfection helps in choosing a method appropriate for the risk, location, and size of the group.

TABLE 7.3 Efficacy and Effectiveness of Point-of-Use Technologies for Household Use in the Developing World Households

Treatment Process	Pathogen	Optimal Log Reduction[a]	Expected Log Reduction[b]	Diarrheal Disease Reduction[c]
Ceramic filters	Bacteria	6	2	63% (51-72%) for candle filters
	Viruses	4	0.5	46% (29-59%) for bowl filters
	Protozoa	6	4	
Free chlorine	Bacteria	6	3	37% (25-48%)
	Viruses	6	3	
	Protozoa	5	3	
Coagulation/ chlorination	Bacteria	9	7	31% (18-42%)
	Viruses	6	2-4.5	
	Protozoa	5	3	
Biosand filtration	Bacteria	3	1	47% (21-64%)
	Viruses	3	0.5	
	Protozoa	4	2	
SODIS	Bacteria	5.5	3	31% (26-37%)
	Viruses	4	2	
	Protozoa	3	1	

[a]Skilled operators using optimal conditions and practices (efficacy); log reduction: pretreatment minus post-treatment concentration of organisms (e.g., 6 log = 99.999% removal).
[b]Actual field practice by unskilled persons (effectiveness). Depends on water quality, quality and age of filter or materials, following proper procedure, and other factors.
[c]Summary estimates from published data. Depends on consistency and correct use of technique, integrity of techniques (e.g., cracked filter), and other household sanitation measures.
SODIS, Solar disinfection.
Data from multiple studies analyzed and summarized by Sobsey 2008; with data from Bielefeldt 2009; Sobsey 2002; WHO 2011(table 7.8).

Definitions

Disinfection, the desired result of field water treatment, means the removal or destruction of harmful microorganisms. Technically, it refers only to chemical means such as halogens, but the term can be applied to heat and filtration.

Pasteurization is similar to disinfection but specifically refers to the use of heat, usually at temperatures below 212°F (100°C), to kill most enteric pathogenic organisms. Disinfection and pasteurization should not be confused with *sterilization*, which is the destruction or removal of all life forms. The goal of disinfection is to achieve *potable* water, indicating that a water source, on average over a period of time, contains a "minimal microbial hazard," so the statistical likelihood of illness is minimized.

Purification is the removal of organic or inorganic chemicals and particulate matter to remove offensive color, taste, and odor. It is frequently used interchangeably with disinfection (e.g., Environmental Protection Agency [EPA] classification of water purifier), but purification, as used here, may not remove or kill enough microorganisms to ensure microbiologic safety.

Heat

The advantages of heat for water disinfection are the following:

- It is widely available.
- It imparts no additional taste to the water.
- It inactivates all enteric pathogens.
- Efficacy of heat treatment is not compromised by contaminants or particles in the water, as in the case of halogenation and filtration.

The major disadvantages of heat are the following:

- Heat does not improve the taste, smell, or appearance of poor-quality water.
- In many areas natural fuel is scarce or unavailable; 1 kg of wood is required to boil 1 L of water.
- Liquid fuels are expensive for developing countries and heavy to carry for the wilderness traveler.

Heat inactivation of microorganisms is exponential and follows first-order kinetics. Thermal death point is reached in a shorter time at higher temperatures, whereas temperatures as low as 140°F (60°C) are effective with a longer contact time. Pasteurization uses this principle to kill food-borne enteric food pathogens and spoiling organisms at temperatures between 140 and 158°F (60-70°C), well below boiling.

Heat resistance varies with different microorganisms, but common enteric pathogens are readily inactivated by heat (**Table 7.4**). Bacterial spores (e.g., *Clostridium* spp.) are the most resistant; some can survive 212°F (100°C) for long periods. *Clostridium* spores are wound pathogens that are ubiquitous in soil, lake sediment, tropical water sources, and the stool of animals and humans. Water sterilization is not necessary for drinking, since these most resistant organisms are not water-borne enteric human pathogens.

Protozoan cysts, including *Giardia*, *Entamoeba histolytica*, and *Cryptosporidium* are sensitive to heat, killed rapidly at 131-140°F (55-60°C). Parasitic helminth eggs and larvae, and cercariae of schistosomiasis, are equally susceptible to heat.

Vegetative bacteria and most enteric viruses are killed rapidly at temperatures above 140°F (60°C) and within seconds by boiling water. Typical pasteurization processes include heating to 145-149°F (63-65°C) for up to 30 min or flash pasteurization using high temperature-short time at 160-162°F (71-72°C) for 15-30 seconds. Recent data confirm

TABLE 7.4 Data on Heat Inactivation of Microorganisms[a]

Organism	Lethal Temperature/Time
Giardia	131°F (55°C) for 5 min
	212°F (100°C) immediately
Entamoeba histolytica	Similar to *Giardia*
Nematode cysts Helminth eggs, larvae, cercariae	122-131°F (50-55°C) (time not specified but should be similar to *Cryptosporidium*)
Cryptosporidium	113-131°F (45-55°C) for 20 min
	148°F (64.2°C) for 2 min
	162°F (72°C) heated up over 1 min
Escherichia coli	131°F (55°C) for 30 min
	140-144°F (60-62°C) for 10 min
Salmonella and *Shigella*	149°F (65°C) for <1 min
Vibrio cholerae	212°F (100°C) for 30 s
Enteric viruses	131-140°F (55-60°C) for 20-40 min
	158°F (70°C) for <1 min
	167°F (75°C) for <0.5 min
Hepatitis A	185°F (85°C) for 1 min
	140°F (60°C) for 10 min
Hepatitis E	140°F (60°C) for 30 min
Bacterial spores	>212°F (100°C)

[a]Endpoint in most studies is death of 100% of organisms. Some studies use 99.9% inactivation, but longer time in contact with heat will rapidly result in inactivation of all micro-organisms.

TABLE 7.5 Boiling Temperature and Altitude

Elevation	Boiling Point of Water
10,000 ft (3048 m)	194° F (90° C)
14,000 ft (4267 m)	187° F (86° C)
19,000 ft (5791 m)	178° F (81° C)

that common water-borne enteric viruses, including hepatitis A virus (HAV), are readily inactivated at these temperatures.

In recognition of the difference between pasteurizing water for drinking purposes and sterilizing for surgical purposes, most sources now agree that boiling for 10 min is not necessary. Heating water on a stove or fire takes time, which counts toward disinfection while the temperature rises from 131° F (55° C) to the boiling temperature. Although attaining boiling temperature is not necessary, it is the only easily recognizable endpoint without using a thermometer. Therefore, any water brought to a boil should be adequately disinfected. For an extra margin of safety, the water should be brought to a boil, the stove turned off, and the pot covered for a few minutes before using the water. The WHO concurs with this conclusion, but the Centers for Disease Control and Prevention (CDC) and the EPA still recommend boiling for 1 min to allow for an extra margin of safety. The boiling point decreases with increasing altitude, but this is not significant with regard to the time and temperature required for thermal death (**Table 7.5**).

The use of hot tap water, "too hot to touch," has been suggested to prevent traveler's diarrhea in developing countries. However, testing shows considerable variation in the temperature of hot tap water (most between 131 and 140° F (55-60° C), but some lower) and in maximum tolerated temperature-to-touch (below 131° F (55° C) for some people). If no other means of water treatment is available, using hot tap water that has been kept hot in a tank for some time is a reasonable alternative. Travelers staying in hotels or other accommodations with electricity can conveniently bring water to a boil with a small electric heating coil or with a lightweight electric beverage warmer brought from home.

In hot, sunny climates, temperatures adequate for pasteurization can be achieved by solar heating using a solar oven or simple reflectors.

Filtration

Many commercial products are available for individuals and groups to filter water in the field. Advantages of filtration include:

- Filters are simple to operate.
- Filters add no unpleasant taste, and many will improve the taste and appearance of water.
- Most filters require no holding time, and water can be consumed as it comes out of the filter.
- It may be rationally combined with halogens if the filter is not rated for viral removal.

Disadvantages of filtration include:

- It is expensive compared with halogen treatment.
- Filters can be heavy and bulky, which may be significant if carrying the gear oneself.
- Many filters will not remove viruses sufficiently and may require a second step with halogens to assure viral inactivation.
- A cracked filter element or a leaking seal can allow channeling of water around the filter and will let contaminated water pass through the device.
- Filters clog quickly if the water is dirty or has a lot of suspended particles and eventually will clog from filtering even "clear" surface water. Most micropore filters include a prefilter for larger particulates. Laboratory paper filters with a pore size of about 20-30 μm or even coffee filters can be used to prefilter the larger particulate debris from dirty water and may also retain parasitic eggs and larvae (see the section on Clarification below for other methods). The user should know how to clean or replace the filter elements to re-establish flow.

TABLE 7.6a Levels of Filtration

Filtration Level	Minimal Pore Size (μm)	Particles Removed
Microfiltration	0.1	Protozoa, bacteria, algae, particles, sediment
Ultrafiltration	0.001	Viruses, colloids, some dissolved solids
Nanofiltration	0.0001	All microorganisms, dissolved substances, salts, endotoxins
Reverse osmosis	0.00001	All of above plus monovalent ions and nearly all organic molecules

TABLE 7.6b Susceptibility of Microorganisms to Filtration

Organism	Approximate Size (μm)	Maximum Filter Pore Size (μm)
Nematode eggs	30 × 60	20
Giardia	6-10 × 8-15	3-5
Entamoeba histolytica	5-30 (average 10)	3-5
Cyclospora	8-9	3-5
Cryptosporidium oocysts	2-6	1
Enteric bacteria	0.5 × 3-8	0.2-0.4
Viruses	0.03	0.01

The effectiveness of filters depends on pore size (**Tables 7.6a and 7.6b**), but other variables influence filter efficiency, including the characteristics of the filter media and the water, as well as flow rate. Microfilters are effective for removing protozoa and bacteria, algae, most particles, and sediment but allow dissolved material, small colloids, and some viruses to pass through. Ultrafiltration membranes are required for complete removal of viruses, colloids, and some dissolved solids. Nanofilters can remove other dissolved substances, including salts (sodium chloride) and endotoxins from water. Reverse osmosis removes monovalent ions (desalination) and nearly all organic molecules.

Filtration is usually a two-step process: physical (separation of particles from liquid) and chemical (attachment of microorganisms to the medium), which may allow increased efficacy of virus removal. Most field filters are not membranes but rather depth filters, with maze-like passageways that trap particles and organisms smaller than the average passage diameter.

Most field devices are microfilters that are adequate for cysts and bacteria but may not sufficiently remove viruses, which are a major concern in water with high levels of fecal contamination. It is important for point-of-use filters to achieve the EPA standard of 4-log reduction (99.99%) of viruses, given the small infectious dose. Most viruses adhere to larger particles or clump together into aggregates that may be removed by the filter, in addition to any electrochemical adherence to the filter media. Reverse osmosis filters that desalinate will also remove viruses; however, these are currently too expensive and slow for use in a hand pump for land travel. Iodine resin filters will kill bacteria and viruses by contact with the iodine, not by mechanical filtration. Several portable filters have test results that meet the EPA standards for removal of viruses: General Ecology First-Need mechanical microfilter claims electrochemical removal of viruses; Sawyer Water Purifier, Lifestraw, MSR and other products that use hollow fiber membrane filtration remove viruses with ultrafiltration capability.

Some filters can be readily and inexpensively built in developing areas. One is a ceramic filter shaped like a flower pot or rounded cone made from local substances like porous fired clay (diatomaceous earth). The other is a biosand filter that uses successive layers of progressively more coarse sand and gravel. The uppermost layer of fine sand further builds a biologic layer that contributes to the filtration effectiveness.

If the water supply is suspected of being heavily contaminated with biologic wastes and additional assurance is needed, then a second step with chemical treatment of the water before or after filtration can kill viruses. Many filters contain a charcoal stage that will remove the halogen, if applied prior to filtration. Alternately, prior filtration allows lower halogen doses to be used for the chemical inactivation step.

Filters for international and wilderness travelers are listed in **Table 7.7**.

CLARIFICATION

The appearance of cloudy water can be improved by several other means. Large particles will settle out over a period of several hours by *sedimentation*. The supernatant can then be filtered and/or chemically treated. Smaller suspended particles can be removed by *coagulation-flocculation*. A pinch of alum, an aluminum salt, is added to a gallon of water, mixed well, and then stirred occasionally for 30-60 min. The quantity added does not need to be precise, and more can be used as needed. The small particles clump (flocculate) and then settle out over minutes to hours. The supernatant is then decanted, or the mixture is poured through a paper filter before proceeding with microfiltration and/or chemical treatment. Coagulation-flocculation removes many microorganisms as well as other impurities from the water, greatly improving taste, smell, and microbiologic safety of cloudy water. However, coagulation-flocculation should not be used as a sole step for disinfection; it should be followed by chemical treatment, filtration, or ultraviolet treatment.

Granular Activated Charcoal

Granular activated charcoal (GAC) improves water quality by removing organic pollutants and chemicals by adsorption. GAC can remove objectionable color, taste, and smell from water. Although some microorganisms will adhere to GAC or become trapped in charcoal filters, GAC does *not* remove all microorganisms; thus, it does not disinfect. In fact, charcoal beds become colonized rapidly with nonpathogenic bacteria. One rational use of GAC is to remove the color and taste of iodine or chlorine after disinfection. If used to remove halogen, one must wait until *after* the required contact time before running water through charcoal or adding charcoal to the water. Granular activated charcoal is commonly incorporated into point-of-use water filters (**Table 7.7**).

CHEMICALS

Chemical means of disinfection include the halogens, chiefly chlorine and iodine, and their chemical species that form in aqueous solution, e.g., hypochlorite. Chlorine dioxide is also considered in this section.

Halogens (chlorine and iodine) have the following advantages:

- They are excellent disinfectants for bacteria, viruses, *Giardia*, and amebic cysts.
- Iodine and chlorine are widely available in several forms.
- They are inexpensive.
- They can be applied with equal ease to large and small quantities of water, and dosing is flexible.
- Taste can be removed.

Disadvantages include:

- They can potentially be toxic (mainly iodine).
- Taste can be unpleasant at concentrations of 4-5 mg/L and above.
- The potency of some products (tablets and crystals) is affected by prolonged exposure to moisture, heat, and air.
- Liquids are corrosive and stain clothing.
- Iodine and chlorine do not kill *Cryptosporidium* when used in usual field doses.

TABLE 7.7 Portable Field Water Filters and Purification Devices

Manufacturer, Product/ Manufacturer's Website[a]	Microbial Claims[b]	Operation	Primary Filter, Additional Elements, Stages, Comments[c]	Capacity	Retail Price (US$)[d]
Aquamira www.mcnett.com Water filter bottle and Frontier	P, B, V	In line, drink-through in sport bottle, water bag, or gravity drip	Prefilter, porous plastic microfilter, new Redline filter for virus removal, carbon shell. May be used in conjunction with Aquamira water treatment—chlorine dioxide stabilized solution	1-2 people	20-50
Aquarain www.aquarain.com					
Aquarain 200 and 400	P, B	Gravity drip	Stacked bucket filter with one to four candle filters with ceramic elements. Carbon core, stainless steel housing	Small group	240-320
British Berkfeld www.jamesfilter.com					
Big Berkey and multiple other models	P, B	Gravity drip	Bucket filter, one to four ceramic elements with carbon matrix or candle filters of compressed carbon. Available in stainless steel or Lexan housing with 1.5-6 gallon lower reservoir.	Household or moderate-sized group	240 (100-320)
General ecology www.generalecology.com			Claims for viral removal are based on electrostatic attraction in structured matrix compressed carbon block filter. Variety of sizes and configurations also available for in-line use and electric-powered units		
First Need XLE	P, B, V	Hand pump	Compressed charcoal	Small group	120
Base camp	P, B, V	Hand pump or electric	Compressed charcoal element similar to First Need. High flow, high capacity. Stainless steel housing. Prefilter. Electric models also available	Large group	700
Trav-L-Pure	P, B	Hand pump	Same compressed charcoal filter element as First Need in plastic housing	Small group	230

Hydro-photon www.hydro-photon.com		Hand-held purifier	Ultraviolet purifier uses batteries with timer. Active end of unit is held in bottle or other small container of water.	1-2 people	
Multiple Steripen models: Classic Opti Adventurer Ultra Freedom Aqua	P, B, V		Units differ in size, battery (AA, CR 123, rechargeable), LED display, and other features.		50-100
Katadyn www.katadyn.com			Unless otherwise specified, filter elements are 0.2 µm ceramic depth filter.		
My Bottle	P, B, V	Sport bottle	Iodine resin with filter for protozoan cysts, and granular activated charcoal	1-2 people	40-60
Hiker and Hiker Pro	P	Hand pump	Pleated glass-fiber 0.3-µm filter with granular activated charcoal core and prefilter; for high-quality source water, removes “most” bacteria	1-2 people	60-85
Gravity Camp and Basecamp	P, B	Gravity drip	Pleated glass fiber 0.3 µm with activated carbon; reservoir bag with in-line filter	Small group	60
Mini	P, B	Hand pump	Ceramic filter with prefilter	1-2 people	90
Pocket	P, B	Hand pump	Ceramic filter with prefilter	Small group	300
Ceradyn and Gravidyn	P, B	Gravity drip	Bucket filter, three ceramic candles; optional activated carbon core filters with Gravidyn	Small-large group	160-190
Combi	P, B	Hand pump	Ceramic filter and activated carbon cartridge; can be converted for in-line faucet use	Small group	180
Expedition	P, B	Hand pump	Ceramic filter with intake pre-filter; stainless steel housing	Large group	1250
Survivor 06 Survivor 35 (power units also available)	P, B, V	Hand pump	Reverse osmosis filter; desalinates as well as disinfects, for ocean survival; very low flow rate; power units available	1-2 people	1000-2200

Continued

TABLE 7.7 Portable Field Water Filters and Purification Devices—cont'd

Manufacturer, Product/ Manufacturer's Website[a]	Microbial Claims[b]	Operation	Primary Filter, Additional Elements, Stages, Comments[c]	Capacity	Retail Price (US$)[d]
Cascade Designs www.cascadedesigns.com					
MSR Sweetwater microfilter	P, B	Hand pump	0.2-µm depth filter with granular activated carbon and pre-filter; purifier solution (chlorine) as pre-treatment to kill viruses	Small group	90
Miniworks EX	P, B	Hand pump	Ceramic filter with activated carbon core and pre-filter	Small group	90
HyperFlow and AutoFlow	P, B	Pump or gravity drip	Microfilter (0.2 µm) with hollow-fiber technology	Small group	100-120
Guardian	P,B,V	Hand pump	Hollow fiber technology with 0.02 micron pore size to remove viruses.	Small group	350
Sawyer www.sawyerproducts.com					
Water filter Point One Biologic (available in wide array of packaged products)	P, B	Multiple applications including sport bottle and in-line cartridge, gravity drip, bucket filter, or faucet attachment	Hollow-fiber technology, 0.1 µm in versatile filter cartridge	1-2 people or small group	40-90
Water purifier Zero Point Two (available in wide array of packaged products)	P, B, V	Multiple applications, same as Point One filter	Hollow-fiber technology, 0.02 µm, in versatile filter cartridge	1-2 people or small group	130-220

[a] This is not a comprehensive list. Models change frequently. A manufacturer's website is provided if it contains product information; otherwise, search manufacturer and brand with any major search engine to find large retail sites that provide detailed product information.
[b] *B,* Bacteria; *P,* protozoa; *V,* viruses.
[c] Consider additional features, such as flow rate, filter capacity, size, and filter weight.
[d] Prices vary.

- There is some degree of imprecision because the actual residual concentration (after halogen demand is met) is not known.
- Some understanding of the process is helpful to achieve reliable results and reasonable taste.

Vegetative bacteria are markedly sensitive to halogens. Viruses and *Giardia* are sensitive but require higher concentrations or longer contact times. *Cryptosporidium* cysts are highly resistant to halogens. Little is known about *Cyclospora*, but it is assumed to be similar to *Cryptosporidium*. Certain parasitic eggs, such as *Ascaris*, are also resistant, but these are not commonly spread by water. (All these resistant cysts and eggs are susceptible to heat or filtration.)

Primary factors determining the rate and proportion of microorganisms killed are the concentration of halogen (measured in mg/L) or the equivalent, parts per million (ppm), and the length of time organisms are exposed to the halogen (contact time, measured in minutes) (**Table 7.8**). An increase in either halogen concentration or contact time allows a decrease in the other. Theoretically, for given conditions of temperature and pH, doubling contact time allows half the concentration of halogen to achieve the same results. In clear water, this principle can be used to decrease the taste of halogen. Due to many unknown factors in the field, extending contact time even longer adds a margin of safety.

Secondary factors are temperature of the water, organic contaminants in the water, and pH. Cold slows reaction time, so in cold water, the contact time should be increased. Alternatively, the dose could be increased in cold water. Some halogen is absorbed by organic impurities in the water, so an increased dose is required if water is cloudy (high turbidity); longer contact time may not be effective. The better solution is clarification prior to use of halogen. Although clear surface water probably requires minimal halogen, some impurities (at least 1 mg/L) must be assumed, so it is prudent to use 4 mg/L as a target halogen concentration for clear water and to allow extra contact time, especially if the water is cold. Water pH usually becomes a factor only in highly alkaline waters but not for usual surface water, which is neutral to slightly acidic.

TABLE 7.8 Experimental Data for 99.9% Kill with Halogens at pH 6-8

Organism	Halogen	Concentration (mg/L)	Time (min)	TEMPERATURE	
				(° C)	(° F)
Giardia	Chlorine	4.0	60	3-5	37-41
		8.0	30	3-5	37-41
		3.0	10	15	59
		1.5	10	25	77
	Iodine	1.5	10	25	77
		3.0	15	20	68
		7.0	30	3	37
Enteric viruses	Chlorine	0.5	40	2	36
		0.3	30	25	77
	Iodine	0.3	30	25	77
Norovirus	Free chlorine	1	10	5	10
		5	20 seconds	5	2.7
Poliovirus	Iodine	20	1.5	25	77
Escherichia coli	Chlorine	0.03	5	2-5	36-41
	Iodine	1.0	1	2-5	36-41
Cryptosporidium	Chlorine	80	90		

Recommendations for chlorine and iodine disinfection of water with regard to concentration, temperature, and contact times are given in **Table 7.9**. Both chlorine and iodine are available in liquid and tablet form. **Table 7.10** describes some commercially available halogen products.

Choice of Halogen

Iodine has some advantage over chlorine for field disinfection. Dilute iodine solutions are less affected by nitrogenous wastes or pH, and most people prefer the taste at treatment levels. However, there is concern over physiologic activity. Some alteration in thyroid

TABLE 7.9 Halogen Disinfection of Water

Iodine Products	Amount to Release 4 ppm in 1 L	Amount to Release 8 ppm in 1 L[a]
Iodine tabs	½ tab	1 tab
Tetraglycine hydroperiodide	*or*	
EDWGT	1 tab in 2 L	
Potable aqua		
Globaline		
2% Iodine solution (tincture) (do not use decolorized iodine)	0.2 mL; 5 gtt	0.4 mL; 10 gtt
10% Povidone-iodine solution	0.35 mL; 8 gtt	0.70 mL; 16 gtt
Saturated iodine crystals in water (Polar Pure)	13 mL	26 mL
Chlorine Products[b]	**Amount for 5 ppm in 1 L**	**Amount for 10 ppm in 1 L**
Household bleach (5% sodium hypochlorite)	0.1 mL 2 gtt	0.2 mL 4 gtt
Household bleach (8.25%)	1 gtt	2 gtt
Chlorination–flocculation	1 tablet in 2 L	1 tablet (8 ppm)
Chlor-Floc		
AquaCure		

Contact time in minutes at various water temperatures[c]

Concentration of Halogen	5° C	15° C	30° C
2 ppm	240	180	60
4 ppm	180	60	45
8 ppm	60	30	15

[a]For cloudy water, it is preferable to clarify water prior to using halogens to reduce the need for high levels of halogen, improving the taste. For cold water, use the lower dose and increase the contact time.

[b]Formula for calculation of chlorine dose to achieve specific halogen concentration in large volumes of water (from Lantagne 2014):

$$\text{Dose}\,(\text{mg}_{\text{Cl}}/\text{L}_{\text{water}}) = \left(\text{bleach concentration}\,(\%) \times \frac{10{,}000\,\text{mg}_{\text{Cl}}/\text{L}_{\text{Cl}}}{1\%} \times \text{bleach added}\,(\text{mL}_{\text{Cl}}) \times \frac{1\,\text{L}_{\text{Cl}}}{1000\,\text{mL}_{\text{Cl}}}\right) \Big/ (\text{volume of water}\,(\text{L}_{\text{water}}))$$

[c]Recent data indicate that very cold water requires prolonged contact time with iodine or chlorine to kill *Giardia* cysts. These contact times in cold water have been extended from the usual recommendations to account for this and for the uncertainty of residual concentration.

EDWGT: Emergency Drinking Water Germicidal Tablets.

TABLE 7.10 Commercial Halogen Products[a]

Saturated solution of iodine in water

Polar Pure

Iodine crystals, 8 g in 3-oz bottle; bottle cap is used to measure; directions and color dot thermometer on bottle (temperature affects iodine concentration in bottle); capacity: 2000 quarts; weight: 5 oz; yields 4 ppm iodine when recommended dose is added to 1 quart of clean water. Warm water to 20° C (68° F) before adding iodine to shorten contact time. Since it is not feasible to warm all water, extend contact time to 1-2 h for very cold water.

Saturated aqueous solution of crystalline iodine is an excellent and stable source of iodine.

Iodine Solutions

Iodine solutions for topical disinfection can be used for water; however, these solutions also contain iodide, which has physiologic activity but no disinfection activity:

Tincture of iodine: 2% iodine, 2.4% iodide

Lugol's solution: 5% iodine, 10% iodide

Strong iodine: 2% iodine, 9.0% iodide

Decolorized iodine: 0% iodine

Betadine solution contains 9-12% iodine bound to a large neutral molecule that serves as a sustained-release reservoir of free iodine, resulting in 2-10 ppm free iodine in aqueous solution.

Iodine tablets

Potable Aqua (Wisconsin Pharmacal, Jackson, WI)

Emergency Drinking Water Germicidal Tablets (Coghlan's, Winnipeg, MB, Canada, www.coghlans.com)

Iodine-containing tablets (tetraglycine hydroperiodide) release approximately 7-8 mg iodine when added to water. One tablet is added to 1 quart of water. In cloudy or cold water, add two tabs. Contact time is only 10-15 min in clear, warm water, much more in cold, cloudy water. Neutralizing tablets contain ascorbic acid.

This method was developed by the military for troops in the field. Advantages are unit dose and short contact time, but these concentrations create strong tastes that are not acceptable to many users. Options to improve taste include adding one tablet to 2 quarts of clear water to yield about 4 mg/L (and extend contact time), or using the neutralizer tablets. Clarify cloudy water first.

Flocculation plus chlorination

Chlor-Floc (Deatrick & Associates, Alexandria, VA)

PUR, Purifier of Water (Proctor and Gamble, Cincinnati, OH, http://www.pghsi.com/safewater/development.html)

Aqua Cure (distributed by Safesport Manufacturing, Denver, CO)

Tablets or powder that contain a flocculating agent and source of chlorine to clarify and disinfect water. The process was developed and tested by the military and is still used by some services for individual troops in the field. Chlor-Floc and Aqua Cure are similar products containing sodium dichloro-isocyanurate (NaDCC) with proprietary flocculating agents and a buffering system. A cloth filter is provided. One tablet provides 8 ppm available chlorine. Proctor and Gamble recently developed packets of powder for humanitarian use in developing countries or disaster situations that contains ferric sulfate as a coagulant and calcium hypochlorite.

Household bleach (sodium hypochlorite)

The Centers for Disease Control and Prevention (CDC) and World Health Organization (WHO) advocate chlorination for point-of-use household water disinfection, using a 1% hypochlorite solution to provide a dosage of 1.875 or 3.75 mg/L of sodium hypochlorite with a contact time of 30 min.

Continued

TABLE 7.10 Commercial Halogen Products—cont'd

NaDCC (chlorine)

Aquaclear (Gal Pharm, Ireland, imported by BCB Survival Equipment)

Aquatabs (Global Hydration Water Treatment Systems, Kakabeka Falls, Ontario, Canada)

NaDCC is a stable, nontoxic chlorine compound that forms a mildly acidic solution, which is optimal for hypochlorous acid, the most active disinfectant of the free chlorine compounds. Free chlorine is in equilibrium with available chlorine that remains in compound, providing greater biocidal capacity. NaDCC is more stable and provides more free, active chlorine than other available chlorine products for water disinfection. Available as individually wrapped effervescent tablets for small quantities or in bulk quantities and higher concentrations in screw-cap tubs for disinfection of large quantities of water or for shock chlorination of tanks and other storage systems.

Calcium hypochlorite (dry chlorine)

Calcium hypochlorite is a stable, concentrated, dry source of hypochlorite that is commonly used for chlorination of swimming pools. It is widely available in tablets or tubs of granules through chemical supply or swimming pool supply stores.

Redi-Chlor (Continental Technologies, Little River, KS) distributes calcium hypochlorite tablets in blister packs that come in different strengths and can be broken in half or fourths to treat various quantities of water. Recommended dose results in 2-5 mg/L residual chlorine. This is a convenient source of hypochlorite, which can also be used for superchlorination.

Silver

Micropur (www.katadyn.com)

Silver in tablet, liquid, or crystal form. Unit dosages available for small volumes of water or for big storage tanks. Most common formulation: silver-containing tablets in individual bubble packing; add one tab to 1 quart of water. Mix thoroughly and allow 2 h contact time.

Claims: “For the disinfection and storage of clear water.” “Reliably kill bacterial agents of enteric diseases but *not* worm eggs, ameba, viruses.” “Neutral to taste, simple to use and innocuous.” Treatment of water will ensure protection against reinfection for 1-6 months.

Silver is approved by the EPA to be marketed in the USA as a “water preservative” that can maintain bacteria-free water for up to 6 months. Although there are proven antibacterial effects, silver tablets are not licensed as a water purifier in the United States. Note there are no claims for viruses and protozoa, because concentrations may not be adequate to kill these organisms.

Silver and chlorine

Micropur Forte (Katadyn Corporation, Wallisellen, Switzerland, www.katadyn.com)

This product combines silver and chlorine in tablet or liquid form. Chlorine ensures destruction of viruses and bacteria in clear, untreated surface water. Silver maintains microbiologic purity of water for up to 6 months. If water is consumed right away, there is no reason to use this product, because the silver adds little advantage to chlorine alone.

Chlorine dioxide

Aquamira (McNett Outdoor, Bellingham, WA)

Pristine (Advanced Chemicals, Vancouver, British Columbia)

MicroPur MP-1 (Katadyn Corporation)

Various products in tablet, liquid, or powder form containing “stabilized” chlorine dioxide that generates active disinfectant through mixing two ingredients or through dissolution of the tablets in water. Advantages of chlorine dioxide are greater effectiveness than chlorine at equivalent doses and the ability to inactivate *Cryptosporidium* oocysts with reasonable doses and contact times. Chlorine dioxide does not have extended persistence in water, so should not be used to maintain microbiologic purity of stored water. Testing suggests tablets may be more effective than solutions.

[a]Extensive data exist for the effectiveness of iodine and chlorine (see text and Table 7.9)

function can be measured when iodine is used for water disinfection, and goiters have been associated with excessive iodine levels in water. There is the potential for hypersensitivity reactions (although these have not been described for iodinated water) and for exacerbation of pre-existing thyroid problems.

Therefore iodine use is *not* recommended in the following circumstances:

- Unstable thyroid disease
- Known iodine allergy
- During pregnancy for periods longer than several weeks (because of the risk of neonatal goiter).

Despite studies documenting use of iodine for prolonged periods without problems, WHO recommends limiting iodine water disinfection to emergency use of a few weeks. The military developed iodine tablets and still uses them in some situations, but the disadvantages of unpleasant taste and color and alteration of thyroid function have led them to substitute chlorine tablets combined with a flocculent for many small group field applications.

Taste of halogens may be improved by the following:

- Using GAC *after* contact time (included as a final stage in many filters)
- Reducing the halogen concentration and increasing the contact time in clean water
- Removing taste by chemical means. A tiny pinch or several granules of ascorbic acid (vitamin C, available in powder or crystal form) or sodium thiosulfate (nontoxic, available at chemical supply stores) will reduce iodine to iodide or chlorine to chloride, which has no taste or color; these must be added *after* the required contact time. Many flavored drink mixes contain ascorbic acid. Note that iodide still has physiologic activity. Hydrogen peroxide will also reduce chlorine to chloride (see the section on Superchlorination-Dechlorination below).

Superchlorination-Dechlorination

The above principle of chemical reduction is used in this process. Chlorine (hypochlorite) can be used in very high doses of 100-200 mg/L for reliable disinfection, then dechlorinated (reducing hypochlorite to chloride), effectively removing taste and smell with no toxicity. This is an extremely effective way to maintain potability of water stored for prolonged periods, dechlorinating batches as needed. It is also a very good technique for disinfecting large quantities of water. There are currently no commercial products using this technique; however, ingredients can be purchased from chemical supply (30% peroxide) and swimming pool supply (calcium hypochlorite granules) stores.

About ¼–½ tsp/L of calcium hypochlorite (65% available chlorine) is added to water to achieve very high concentrations of chlorine for disinfection, tested only by strong smell. After a reasonable contact time of 30-60 min, add about 6 drops 30% hydrogen peroxide (usual wound care strength is 3%) and stir or agitate, which causes formation of soluble nontoxic calcium chloride. Excess peroxide bubbles off as oxygen, but hydrogen peroxide is also a disinfectant. If titrated correctly, treated water has no chlorine taste. Ingredients should be kept in separate 3-4 oz plastic bottles and are highly stable if kept in a cool, dry place. Measurements do not need to be exact, but it takes some experimentation and experience to balance the two and achieve optimal results. Hydrogen peroxide 30% is extremely corrosive and burns skin, so handle cautiously.

Iodine Resins

Iodine resins are considered a contact disinfectant: iodine binds to microorganisms that come into contact with the resin aided by electrostatic forces, but leaves only small amounts of iodine dissolved in the water. Organisms are effectively exposed to high iodine concentrations when passing through the resin, allowing reduced contact time; however, some contact time is necessary. *Cryptosporidium* oocysts may become trapped in the resin, but of those passing through, half are viable at 30 min.

The resins have been incorporated into many different filter designs available for field use. Most contain a 1-μm cyst filter, which should effectively remove *Cryptosporidium* as well as *Giardia* and any other halogen-resistant parasitic eggs or larva. Their operation assumes that resins kill bacteria and viruses rapidly and the filter membrane removes cysts, so minimal contact time is required for most water. A carbon stage removes residual dissolved iodine to prevent excessive iodine ingestion in long-term users. The effectiveness of an individual resin matrix depends on ensuring contact of every microorganism with iodine resin (no channeling of water). Cloudy or sediment-laden water may clog the resin, as it would with any filter, or coat the resin, inhibiting iodine transfer. Due to variable test results and amounts of ingested iodine, most models are no longer marketed in the United States; however, some products are still available for international use.

Chlorine Dioxide

Chlorine dioxide (ClO_2), a potent biocide, has been used for many years to disinfect municipal water and in numerous other large-scale applications. Until recently, chlorine dioxide could be used only in large-scale water treatment applications, but several new chemical methods for generating chlorine dioxide on-site can now be applied in the field for small quantity water treatment, allowing this technique to gain wider use for disinfection of both community and point-of-use drinking water supplies in developed countries. Chlorine dioxide is capable of inactivating most water-borne pathogens, including *Cryptosporidium parvum* oocysts, at practical doses and contact times. It is at least as effective a bactericide as chlorine and in many cases superior. It is far superior as a virucide. Chlorine dioxide is not stable in solution and does not produce a lasting residual (**Table 7.10**).

OTHER CHEMICAL DISINFECTANTS

Mixed Species Disinfection (Electrolysis)

Passing a current through a simple brine salt solution generates free available chlorine and other "mixed species" disinfectants that have been demonstrated effective against bacteria, viruses, and bacterial spores. The process can be used on both large and small scales. The resulting solution has greater disinfectant ability than a simple solution of sodium hypochlorite and has even been demonstrated to inactivate *Cryptosporidium*, suggesting that chlorine dioxide (see below) is among the chemicals generated. Testing and large-scale products are available on the Miox website (http://www.miox.com/). The pocket-sized device (Miox Purifier) is no longer marketed, but an individual user product for point of use in developing areas is in production (SE 200 Electrochlorinator) by Cascade Designs (Seattle, WA; http://sites.path.org/water/community-water/products/technology-se200/).

Potassium Permanganate

Potassium permanganate is a strong oxidizing agent with some disinfectant properties. It was used extensively before hypochlorites as a drinking water disinfectant. In some parts of the world, it is still used on a small scale for this purpose and also for washing fruits and vegetables. It is most commonly used as a 1-5% solution for disinfection and often sold as packets of 1 g to be added to 1 L of water. At these concentrations, the solutions are deep pink to purple and can stain surfaces. Although bacterial inactivation can be achieved with moderate concentrations and contact times, it cannot be recommended for field use, since quantitative data are not available for viruses or protozoan cysts.

Hydrogen Peroxide

Hydrogen peroxide (H_2O_2) is a strong oxidizing agent but considered a weak disinfectant for water disinfection use. Small doses (1 mL of 3% H_2O_2 in 1 L water) are effective for inactivating bacteria within minutes to hours, depending on the level of contamination. Viruses require high doses and longer contact times. Lack of data for protozoan cysts and quantitative data for dilute solutions prevents it from being useful by itself as a field water disinfectant. In higher concentrations, it can be used to sterilize industrial and food processing equipment. It is considered safe enough for use in foods, yielding oxygen and water as innocuous end products.

Silver

Silver is widely used as a disinfectant, although the literature on antimicrobial effects of silver is confusing. Silver ion has bactericidal effects in low doses, but disinfection requires several hours at the recommended concentration of 50 ppb. An advantage is absence of taste, odor, and color. One factor limiting its use is that it readily adsorbs to container surfaces, making it difficult to control the concentration. However, this characteristic is also used beneficially, coating surfaces with silver to release small amounts. Another caution is that silver has physiologic activity, but doses used for water treatment are unlikely to cause side effects such as agyria, a permanent discoloration of the skin and mucous membranes. The use of silver as a drinking water disinfectant has been much more popular in Europe, but in the United States, it is approved only for maintaining bacteriological quality of stored water.

Citrus

Citrus juice contains limonene, which has biocidal properties. Lemon or lime juice has been shown to destroy *Vibrio cholerae* at a concentration of 2% (equivalent of 2 tbs/L of water) with a contact time of 30 min. Lime juice also killed 99.9% of *V. cholerae* on cabbage and lettuce leaves and inhibited growth of *V. cholerae* in rice foods, suggesting that adding sufficient lime juice to water, beverages, and other foods can reduce disease risks. Commercial products using citrus cannot yet be recommended as primary means of water disinfection, rather than an ancillary or emergency measure.

Ultraviolet Light

In sufficient doses, all water-borne enteric pathogens are inactivated by ultraviolet (UV) radiation. Bacteria and protozoan parasites require lower doses than enteric viruses and bacterial spores. *Giardia* and *Cryptosporidium* are susceptible to practical doses of UV light and may be more sensitive because of their relatively large size. The germicidal effect of UV light depends on light intensity and exposure time. Advantages of UV treatment include:

- UV irradiation is effective against all microorganisms.
- Treatment does not require chemicals and does not affect the taste of the water.
- It works rapidly, and extra dosing to the water presents no danger; in fact, it is a safety factor.
- Available from sunlight (see section on SODIS below)

Disadvantages include the following:

- UV irradiation with lamps requires a power source and is costly.
- No residual disinfection power; so water may become re-contaminated or re-growth of bacteria may occur.
- Particulate matter can shield microorganisms from UV rays.

UV lamp disinfection systems are widely used to disinfect drinking water at the community and household level. Steri-Pen, a portable, battery-operated UV water disinfection system for individual use has recently been developed (Hydro-Photon, Blue Hill, ME; http://www.hydrophoton.com/). The use of this portable technology is currently limited to small volumes of clear water, but its simplicity is very appealing (**Table 7.7**).

Solar Irradiation (SODIS)

UV irradiation by sunlight in the UV-A range can substantially improve the microbiologic quality of water and thereby reduce diarrheal illness in communities employing this technique in developing countries. Recent work has confirmed the efficacy and optimal procedures of the solar disinfection (SODIS) technique. Transparent bottles (e.g., clear plastic beverage bottles), preferably lying on a dark surface, are exposed to sunlight for a minimum of 4 h; some investigations demonstrate improved benefit from several sequential days. Oxygenation induces greater reductions of bacteria, so agitation is recommended before solar treatment in bottles.

UV and thermal inactivation are synergistic for solar disinfection of drinking water in transparent plastic bottles. Above 55°C (131°F), thermal inactivation is of primary importance. Use of a simple reflector or solar cooker can achieve temperatures of 65°C (149°F), which will pasteurize the water (see section on Heat disinfection).

Where strong sunshine is available, solar disinfection of drinking water is an effective, low-cost method for improving water quality and may be of particular use in refugee camps and disaster areas.

Nanoparticles: Solar Photocatalytic Disinfection

Several nanomaterials have been shown to have strong antimicrobial properties and are being evaluated for use in water disinfection and purification. They are already being used widely in industrial purification, but they show great potential for point-of-use applications as well. The metals, including silver, titanium dioxide (TiO_2), and zinc oxide, are of particular interest for water disinfection applications because they can be activated by UV light to produce potent oxidizers. In addition to being an excellent disinfectant for various microorganisms, this process is unique in its ability to break down complex organic contaminants and most heavy metals into carbon dioxide, water, and inorganics. For field water disinfection, nanoparticles coated with TiO_2 can be integrated into a plastic bag and remain active for hundreds of uses

SUMMARY OF PREFERRED TECHNIQUES

Considerations for choosing a specific field disinfection technique are listed in **Tables 7.11** and **7.12**. The optimal technique for an individual or group depends on the number of

TABLE 7.11 Method(s) of Choice for Various Source Water Conditions

	"Pristine" Wilderness Water with Little Human or Domestic Animal Activity	Tap Water in Developing Country	DEVELOPED OR DEVELOPING COUNTRY	
			Clear Surface Water Near Human and Animal Activity[a]	Cloudy Water
Primary concern	Usually high quality; isolated contamination	Bacteria, *Giardia*, small numbers of viruses	All enteric pathogens, including *Cryptosporidium*	All enteric pathogens and other contaminants that inhibit treatment
Effective methods	Any single-step method[b]	Any single-step method[b]	• Heat or • Filtration plus halogen (can be done in either order) or • Chlorine dioxide or • Ultra Violet (commercial product) or • Filtration with hollow fiber filter rated for viruses	CF followed by second step (heat, filtration, or halogen treatment)

[a]Includes agricultural run-off with cattle grazing, or sewage treatment effluent from upstream villages or towns.
[b]Includes heat, filtration, halogens, chlorine dioxide, or ultraviolet treatment.
CF, Coagulation–flocculation.

TABLE 7.12 Summary of Advantages and Disadvantages of Disinfection Techniques

	Heat	Filtration	Halogens	Chlorine Dioxide	Two-Step Process	UV Treatment
Availability	Wood can be scarce	Many commercial choices	Many products	Several new products generate ClO_2	Filtration plus halogen *or* clarification plus second stage	Portable commercial devises available
Cost	Fuel and stove costs	Moderate expense, but low per unit of water treated	Cheap	Generally inexpensive (depends on method)	Depends on choice of stages	Commercial devices relatively expensive
Effectiveness	Can sterilize or pasteurize	Most filters not reliable for viruses	*Cryptosporidium* and some parasitic eggs are resistant	All pathogenic organisms	Highly effective, should cover all pathogenic organisms	All pathogenic organisms
Optimal application	Clear water	Clear or slightly cloudy; turbid water clogs filters rapidly	Clear; need increased dose if cloudy	Clear water, but ClO_2 less affected by nitrogenous compounds	May be adapted to any source water	Requires clear water, small volumes
Taste	Does not change taste	Can improve taste, especially with charcoal stage	Tastes worse unless the halogen is removed or "neutralized"	Unchanged, may leave some chlorine taste	Depends on sequence and choice of stages; generally improves	Unchanged
Time	Boiling time (min)	Filtration time (min)	Contact time (min–h)	Prolonged to ensure *Cryptosporidium* disinfection	Combination of time for each stage	Min
Other considerations	Fuel is heavy and bulky	Adds weight and space; requires maintenance to keep adequate flow	Works well for large quantities and for water storage. Some understanding of principles is optimal. Damaging if spilled or if container breaks.	More experience and testing would be reassuring. Likely to replace iodine for field use.	More rational to use halogens first if filter has charcoal stage. CF is best means of cleaning very turbid water, then followed by halogen, filtration, or heat.	Sunlight for emergency situations when no other method is available; commercial product for high-quality source water and small groups

CF, Coagulation–flocculation; *UV*, ultraviolet.

persons to be served, space and weight considerations, quality of source water, personal taste preferences, and availability of fuel. Unfortunately, optimal protection for all situations may require a two-step process of (1) filtration or coagulation-flocculation and (2) halogenation, because halogens do not kill *Cryptosporidium* and most filters miss some viruses. In recognition of the need for two-stage treatment of microbiologically contaminated water, many microfilters are packaged with a chlorine solution. Generally the halogen is added first, with filtration as the second step. Heat is effective as a one-step process but will not improve esthetics if the water is cloudy or poor tasting. In addition, fuel supplies may limit the use of heat. Newer techniques generating chlorine dioxide or using ultraviolet light (in clear water) or titanium dioxide nanoparticles are also one-step processes.

When the water will be stored for a period of time, such as on a boat, in a motor home, or as collected rainwater, halogens should be used to prevent the water from becoming contaminated. This can be supplemented before or after storage by filtration. Superchlorination-dechlorination is especially useful in this situation, because high levels of chlorination can be maintained for long periods, and when ready for use, the water can be poured into a smaller container and dechlorinated. If another means of chlorination is used, a minimum residual of 3-5 mg/L should be maintained in the stored water. Iodine will work for short but not for prolonged storage, since it is a poor algaecide. After initial disinfection, silver also can be used to maintain microbiologic quality.

On long-distance, ocean-going boats where water must be desalinated during the voyage, only reverse osmosis membrane filters are adequate.

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