Published in final edited form as:
Wilderness Environ Med. 2019 December ; 30(4 Suppl): S100–S120. doi:10.1016/j.wem.2019.06.006.

Wilderness Medical Society Clinical Practice Guidelines for Water Disinfection for Wilderness, International Travel, and Austere Situations

Howard D. Backer, MD, MPH[1], **Robert W. Derlet, MD**[2], **Vincent R. Hill, PhD**[3]

[1]California Emergency Medical Services Authority, Racho Cordova, CA

[2]Emergency Department, University of California, Davis, Sacramento, CA

[3]Division of Foodborne, Waterborne and Environmental Diseases, Waterborne Disease Prevention Branch, Centers for Disease Control and Prevention, Atlanta, GA

Abstract

To provide guidance to clinicians, the Wilderness Medical Society convened experts to develop evidence-based guidelines for water disinfection in situations where the potability of available water is not ensured, including wilderness and international travel, areas affected by disaster, and other areas without adequate sanitation. The guidelines present the available methods for reducing or eliminating microbiologic contamination of water for individuals, groups, or households; evaluation of their effectiveness; and practical considerations. The evidence evaluation includes both laboratory and clinical publications. The panel graded the recommendations based on the quality of supporting evidence and the balance between benefits and risks or burdens, according to the criteria published by the American College of Chest Physicians.

Keywords

drinking water; water purification; water microbiology; disaster planning; pasteurization; halogens

Introduction

Safe and efficient treatment of drinking water is among the major public health advances of the last century. Without treatment, waterborne diseases can spread rapidly, resulting

---

Corresponding author: Howard D. Backer, MD, MPH, 109 Bonita Ave, Piedmont, CA, 94611; hdbacker@gmail.com.

Author Contributions: Study concept and design (HDB, RWD, VRH); obtaining funding: N/A; acquisition of the data: N/A; analysis of the data: N/A; drafting of the manuscript (HDB, RWD, VRH); critical revision of the manuscript (HDB, RWD, VRH); approval of final manuscript (HDB, RWD, VRH).

Financial/Material Support: None.

Disclosures: None.

Disclaimer
Use of trade names and commercial sources is for identification only and does not imply endorsement by the Centers for Disease Control and Prevention (CDC), the US Department of Health and Human Services (HHS), or the State of California. The findings and conclusions in this report are those of the authors and do not necessarily represent those of CDC or HHS or the State of California.

Supplementary materials
Supplementary material associated with this article can be found in the online version at https://doi.org/10.1016/j.wem.2019.06.006.

in large-scale disease and death.[1,2] In industrialized nations, the population generally is protected from waterborne disease by sophisticated water supply systems that disinfect water and provide continuous monitoring. In contrast, travelers to wilderness and recreational areas anywhere in the world and to underdeveloped regions of some countries may be confronted with untreated or contaminated water that poses a risk of acquiring enteric disease. In addition, disaster situations, such as the 2017 hurricanes that affected Houston, Texas, and Puerto Rico, may result in a breakdown of municipal water systems, exposing victims to non-potable water. These situations necessitate knowledge of how to disinfect water at the point-of-use, prior to drinking.

Methods of water treatment that can be applied in the field include the use of heat, ultraviolet light, clarification, filtration, and chemical disinfection. The choices for the wilderness hiker or international traveler are increasing as new technology is applied to field applications. Different microorganisms have varying susceptibilities to these methods. The risk of waterborne illness depends on the number and type of organisms consumed, host factors, and the efficacy of the treatment system.

Methods

To develop these guidelines, specialists with expertise in wilderness medicine, travel medicine, public health, and microbiology were chosen on the basis of their clinical or research experience. Relevant articles were identified through the PubMed database using the following keywords or phrases: water disinfection, waterborne illness, wilderness water, water filtration, emergency or disaster drinking water treatment. This was supplemented by a hand search of articles from references in the initial PubMed search. Conclusions from review articles were cited in an effort to provide background information and to augment reference selection.

The evidence base for water disinfection has substantial differences from other clinical guidelines. Most of the literature concerning the effectiveness of specific disinfectants and methods against various waterborne microorganisms is laboratory based. Evidence on the benefits of disinfection is either population-based public health research of disease outbreaks or randomized household trials of water disinfection that are influenced by compliance and hygiene. Therefore, the evidence grade is a combination of laboratory, population, and household- or community-level studies.

The authors used a consensus approach to develop recommendations for the disinfection of water. Water treatment techniques and recommendations were not evaluated for the removal of chemicals or toxins. Evidence grades were assigned according to methodology stipulated by the American College of Chest Physicians for grading of evidence and recommendations[3] (online Supplementary Table 1). These recommendations are graded on the basis of the totality of supporting evidence and balance between the benefits and risks or burdens for each modality.

Etiology and Risk of Waterborne Infection

WILDERNESS SETTINGS

Millions of people enter wilderness areas each year and drink surface water. Even in developed countries with low rates of diarrheal illness, regular waterborne disease outbreaks indicate that the microbiologic quality of the water, especially surface water, is not ensured.[4-7] Public health agencies regularly report outbreaks of disease associated with surface water from backcountry and parks as well as from campground water systems. The environment and activity upstream from the travelers' surface water source defines the risk. Side streams draining springs, snowmelt, and glaciers where there is no human or animal activity are lower risk. In contrast, upstream usage by humans, farm animals, or wildlife pose a major risk. Cattle excrete pathogenic strains of *Escherichia coli* and *Salmonella* and have been found in multiple studies to be the major animal species contributing to waterborne disease in North America.[8,9] Giardiasis is a zoonotic infection with numerous host species, including farm animals, deer and other wild ungulates, beavers, and even household animals; however, the extent of transmission to humans is less defined.[10]

Nonalpine wilderness areas in the United States may have streams and rivers that are contaminated with animal waste, including farm animal runoff, or may be contaminated with incompletely treated sewage from towns and urban areas. In many countries, wilderness areas are co-occupied by local populations and domesticated animals that pollute water sources. Because it is very difficult to exclude animal and human activity in the watershed, the Centers for Disease Control recommend treating surface water before ingestion as a precaution to protect health.

INTERNATIONAL TRAVEL

Substantial progress has been made in the past 20 years toward the goal of safe drinking water and sanitation worldwide, particularly in Asia and Latin America[11]; however, 780 million people (11% of world population) still lack a safe water source, and 2.5 billion people lack access to improved sanitation. Africa and Oceania are the regions with the greatest need for improvement. More than 890 million persons still practice open defecation, the largest number being in India and Africa.[11-13] Studies in underdeveloped regions around the world show high levels of microbes in the environment and water sources.[14-18] Contamination of tap water commonly occurs because of antiquated and inadequately monitored waste disposal, water treatment, and distribution systems.[19,20]

In both developed and developing countries, after natural disasters such as hurricanes, tsunamis, and earthquakes, one of the most immediate public health problems is a lack of potable water. Wilderness visitors and international travelers have no reliable resources to evaluate local water system quality. Less information is available for remote surface water sources. Appearance, smell, and taste are not reliable indicators to estimate water safety.

Infectious agents with the potential for waterborne transmission include bacteria, viruses, protozoa, and nonprotozoan parasites. The list of microbial agents is similar to the list of microorganisms that can cause travelers' diarrhea, most of which can be waterborne as well as foodborne. Although the primary reason for disinfecting drinking water is to destroy microorganisms from animal and human biologic wastes, water may also be contaminated with toxins and chemical pollutants from industrial sources or from the environment. *Escherichia coli* and *Vibrio cholerae* may be capable of surviving indefinitely in tropical water. Enteric bacterial and viral pathogens survive in temperate water generally only several days; however, some species such as *E coli* O157: H7 can survive 12 weeks at 25°C.[21] Most enteric organisms, including *Shigella* spp, *Salmonella enterica* serotype Typhi, hepatitis A, and *Cryptosporidium* spp, can retain viability for long periods in cold water and can even survive for weeks when frozen in water.

The risk of waterborne illness depends on the number of organisms consumed, which is in turn determined by the volume of water, concentration of organisms, and treatment system efficiency.[22,23] Additional factors include virulence of the organism and defenses of the host. Microorganisms with a small infectious dose (eg, *Giardia*, *Cryptosporidium*, *Shigella* spp, hepatitis A, enterohemorrhagic *E coli*, and norovirus—the leading viral disease risk in water contaminated with human waste) may cause illness even from inadvertent drinking during water-based recreational activities.[10] Most diarrhea among travelers is probably foodborne; however, the capacity for waterborne transmission should not be underestimated. Because long-lasting immunity does not develop for most enteric pathogens, reinfection may occur.

The combined roles of safe water, hygiene, and adequate sanitation in reducing diarrhea and other diseases are clear and well documented. The World Health Organization (WHO) estimates that 94% of diarrheal cases globally are preventable through modifications to the environment, including access to safe water.[1] Recent studies of simple water interventions in households of developing countries clearly document improved microbiological quality of water, a 30 to 60% reduced incidence of diarrheal illness, enhanced childhood survival, and reduction of parasitic diseases, many of which are independent of other measures to improve sanitation.[24]

General recommendations for drinking water disinfection:

- Treat water when traveling in developing countries. **Evidence grade: 1A**
- Treat water in wilderness areas with nearby agricultural use, animal grazing, or upstream human activity. **Evidence grade: 1A**
- Treat water in wilderness settings without evidence of domestic animal and little to no wildlife or human activity. **Evidence grade: 2B**
- Treat water in disaster situations affecting municipal or private drinking water sources. **Evidence grade: 1A**

Water Treatment Methods

Multiple techniques for improving the microbiologic quality of water are available to individuals and small groups while hiking or traveling. Bottled water may be a convenient and popular solution but creates ecologic problems. Furthermore, in underdeveloped countries, the quality of bottled water may not meet the standards of developed countries and may contain pathogenic microbes.[25]

The term *disinfection*, the desired result of field water treatment, is used here to indicate the removal or destruction of harmful microorganisms, which reduces the risk of illness. This is sometimes used interchangeably with *purification*, but the latter term more accurately indicates the removal of organic or inorganic chemicals and particulate matter to improve color, taste, and odor. Unless specifically designed to remove chemical contaminants, disinfection techniques may not make water safe from chemical exposures. *Potable* implies drinkable water, but it technically means that a water source, on average, over a period of time, contains a minimal microbial hazard so that the statistical likelihood of illness is acceptably low. All standards, including water regulations in the United States, acknowledge the impracticality of trying to eliminate all microorganisms from drinking water. Generally, the goal is a 3 to 5 log reduction (99.9–99.999%), allowing a small risk of enteric infection. Newer standards from the US Environmental Protection Agency (US EPA) and the WHO set target goals to reduce some organisms to zero; however, all enforceable standards allow a small risk for enteric infection.[26]

Product Testing and Rating

Filters are rated by their ability to retain particles of a certain size, which is described by 2 terms. *Absolute* rating means that 100% of a certain size of particle is retained by the filter (ie, filtered-out). *Nominal* rating indicates that > 90% of a given particle size will be retained. Filter efficiency is generally determined with hard particles (beads of known diameter), but microorganisms are soft and compressible under pressure. The US EPA and NSF International are the primary agencies that set standards for disinfection products and protocols for testing to meet these standards.

The US EPA does not endorse, test, or approve mechanical filters; it merely assigns registration numbers that distinguish between 2 types of filters: those that use mechanical means only and those that use a chemical designated as a pesticide. Portable water treatment device claims for microbiologic reduction are based on consensus performance standards that serve as a guideline for testing.[27] Testing is done or contracted by the manufacturer; the US EPA neither tests nor specifies laboratories. Testing must be done with bacteria (*Klebsiella*), viruses (poliovirus and rotavirus), and protozoa (*Cryptosporidium* has replaced *Giardia*). A 3-log reduction (99.9%) is required for protozoan cysts, 4-log reduction (99.99%) for viruses, and 5- to 6-log reduction for bacteria. To be called a microbiologic water purifier, the unit must remove, kill, or inactivate all types of disease-causing microorganisms from the water, including bacteria, viruses, and protozoan cysts, so as to render the processed water safe for drinking. An exception for limited claims may be allowed for units removing specific organisms to serve a definable environmental need, for example, removal of protozoan cysts.[27]

Clarification Techniques

Clarification refers to techniques that reduce the turbidity or cloudiness of water caused by natural organic and inorganic material. (Turbidity is measured in nephelometric turbidity units [NTU].) These techniques can markedly improve the appearance and taste of water. They may reduce the number of microorganisms, but not enough to ensure potable water;

however, clarifying the water facilitates disinfection by filtration or chemical treatment. Cloudy water can rapidly clog filters designed to remove microorganisms. Moreover, cloudy water requires increased levels of chemical treatment, and the combined effects of the water contaminants plus chemical disinfectants results in unpleasant taste.

Adsorption

Granular activated carbon (GAC) is widely used in water treatment. When activated, charcoal's regular array of carbon bonds is disrupted, making it highly reactive for adsorbing dissolved chemicals.[28,29] GAC is the best means to remove toxic organic and inorganic chemicals from water (including disinfection byproducts) and to improve odor and taste.[30,31] Thus, it is widely used in municipal disinfection plants, in household under-sink devices, and in portable water filters. In field water treatment, GAC is best used after chemical disinfection to make water safer and more palatable by removing disinfection byproducts and pesticides, as well as many other organic chemicals and some heavy metals. It removes the taste of chemical disinfectants such as iodine and chlorine.

GAC does not kill microorganisms and is not designed for microbial removal; in fact, bacteria attach to charcoal, where they are resistant to chlorination because the chlorine is adsorbed by the GAC.[30-32]

Sedimentation

Sedimentation is the separation of suspended particles such as sand and silt that are large enough to settle rapidly by gravity. Most microorganisms, especially protozoan cysts, also settle eventually, but this takes much longer.[33] Simply allowing the water to sit undisturbed for about 1 h or until sediment has formed on the bottom of the container and then decanting or filtering the clear water from the top through a coffee filter or finely woven cloth will remove many larger particles from the water. A second method of disinfection must then be used to obtain potable water.

Coagulation–flocculation

Coagulation–flocculation (C-F) is a technique that has been in use since 2000 BC and remains a routine step in municipal water treatment.[34,35] C-F can remove smaller suspended particles and chemical complexes too small to settle by gravity (colloids). Coagulation is achieved with the addition of a chemical that causes particles to stick together by electrostatic and ionic forces. Flocculation is a physical process that promotes the formation of larger particles by gentle mixing. Alum (an aluminum salt), lime (alkaline chemicals principally containing calcium or magnesium with oxygen), or iron salts are commonly used coagulants. Alum is nontoxic and used in the food industry for pickling. It is readily available in most chemical supply stores and some grocery stores. C-F removes 60 to 98% of microorganisms, heavy metals, and some chemicals and minerals.[36,37] The tendency of microorganisms to clump with small particles or clump together to form larger aggregates enhances their removal by C-F. C-F also has the benefit of reducing the amount of chemical disinfectant needed because turbidity increases demand for disinfectants such as hypochlorite.[37-39]

The amount of alum added in the field, approximately 1 large pinch (1 mL or 1/8 tsp) per 4 L (approximately 1 gal) of water, need not be precise. Stir or shake briskly for 1 min to mix, and then agitate gently and frequently for at least 5 min to assist flocculation. If the water is still cloudy, add more flocculent and repeat mixing. After at least 30 min for settling, pour the water through a fine-woven cloth or paper filter. Although most microorganisms are removed with the floc, a final process of microbiologic filtration or chemical disinfection (below) should be completed to ensure disinfection. Several products combine C-F with halogen disinfection, which allows a single-step process.[40-43]

Improvisational techniques for clarification

Many inorganic and organic compounds can be used as a coagulant, including lime (calcium oxide) or potash (from wood ash).[44] In an emergency, bleaching powder, baking powder, or even the fine white ash from a campfire can be used.[45] Other C-F agents used traditionally by native peoples include seed extracts from the nirmali plant in southern India, moringa plants in Sudan, crushed almonds, dried and crushed beans, and rauwaq (a form of bentonite clay).[46]

Adsorbents such as charcoal, clay, and other types of organic matter have been used for water treatment since biblical times.[32] These substances are used as the filter media and also can act as coagulants.[47] Clays can decrease turbidity and microbes in water by about 90 to 95%, but adsorption is not the main action of ceramic or clay filters.

Assessment of supporting evidence:

- Clarification reduces cloudiness, particulate matter, and waterborne microorganisms; improves the taste and esthetics of water; and improves the effectiveness of chemical disinfectants, filtration, and ultraviolet disinfection. However, it does not reliably disinfect if used alone. **Evidence grade: 1A**
- GAC is highly effective at removing taste and odor compounds but is not adequate for microbial removal. **Evidence grade: 1A**
- Sedimentation is effective for removing large particles such as sand and dirt but will not remove suspended or dissolved substances (see C-F). **Evidence grade: 2B**
- C-F removes most microorganisms, but it does not reliably disinfect if used alone. **Evidence grade: 1A**
- Traditional or improvisational C-F techniques (other than alum or those used in municipal disinfection plants) have empiric evidence but do not have robust scientific evidence or practical use guidance and should be used with caution to protect the health of consumers. **Evidence grade: 2C**

Disinfection Methods

HEAT

Heat is the oldest and most reliable means of water disinfection. Heat inactivation of microorganisms is a function of time and temperature (exponential function of first-order kinetics). Thus, the thermal death point is reached in a shorter time at higher temperatures, whereas lower temperatures are effective if applied for a longer time. Pasteurization uses this principle to kill food pathogens and spoiling organisms at temperatures well below boiling, generally between 60°C (140°F) and 70°C (158°F). Flash pasteurization occurs within 30 s at 70 to 72°C (158 to 162°F).[48,49]

All common enteric pathogens are readily inactivated by heat at pasteurization temperatures, although microorganisms vary in heat sensitivity, with protozoan cysts being the most sensitive to heat, bacteria intermediate, and viruses less sensitive (Table 1 [50-62]).[50,51] Only bacterial spores are more resistant, but they are not generally enteric pathogens.[52]

As enteric pathogens are killed within seconds by boiling water rapidly at temperatures > 60°C (140°F), the traditional advice to boil water for 10 min to ensure potable water is excessive. The time required to heat water from 55°C (131°F) to aboil works toward disinfection; therefore, any water brought to a rapid boil should be adequately disinfected.[63] Boiling for 1 min is recommended by the US CDC to account for user variability in identifying boiling points and adds a margin of safety. The boiling point decreases with increasing altitude, but this is not significant compared with the time required for thermal death at these temperatures (Table 2).

Improvisational techniques—In wilderness or travel environments, the main limitation for using heat is availability of fuel. Although attaining boiling temperature is not necessary to kill microorganisms, boiling is the only easily recognizable endpoint without use of a thermometer. Based on microbiologic testing, hot tap water has been proposed as a means of heat disinfection.[64,65]

Most water from hot water taps measured in countries outside the United States measured 55 to 60°C (131 to 140°F).[51] As a rule of thumb, water too hot to touch fell within the pasteurization range, but tolerance to touch is too variable to be reliable.[66]

If no reliable method of water treatment is available, tap water that has been kept hot in a tank for at least 30 min and is too hot to keep a finger immersed for 5 s (estimated 55 to 65°C; 131 to 149°F) is a reasonable alternative. However, this improvisational measure is less useful for hotels that use on-demand water heaters without a hot water tank. Travelers with access to electricity can boil water with either a small electric heating coil or a lightweight electric beverage warmer brought from home. In austere and desperate situations with hot, sunny climate, pasteurization temperature can be achieved with a solar oven or simple reflectors[67,68] (see the Solar UV Disinfection [UV–SODIS] section).

Assessment of supporting evidence:

- Bringing water to boil (100°C/212°F) will kill pathogenic microorganisms. **Evidence grade: 1A**
- Bringing water at 5000 m (16,000 ft) elevation to boil (83°C/181°F) will kill pathogenic organisms. **Evidence grade: 1B**
- Tap water that has been tanked for 30 min or longer and is too hot to touch (60°C) has a significantly reduced number of pathogenic microorganisms, but this cannot be relied on as the sole means of disinfection. Such water may contain increased amounts of lead or other chemicals from the water heater and piping. **Evidence grade: 2B**
- Pasteurization temperatures can be achieved with a solar oven. **Evidence grade: 2B**

ULTRAVIOLET LIGHT

Ultraviolet (UV) radiation and UV lamp disinfection systems are widely used to disinfect drinking water at the community and household levels. At sufficient doses, all waterborne enteric pathogens are inactivated by UV radiation (UVR). UVC light in the range of 200 to 280 nm is the most effective. The germicidal effect of UV light is the result of action on the nucleic acids of microorganisms and depends on light intensity and exposure time. In sufficient doses of energy, all waterborne enteric pathogens are inactivated by UVR.[69] The UV waves must strike the organism, so the water must be free of particles that could act as a shield.[70] The UV waves do not alter the water, but they also do not provide any residual disinfecting power.[71] Bacteria and protozoan parasites generally require lower doses than do enteric viruses and bacterial spores. However, all viruses, including hepatitis A and norovirus, are susceptible, with relatively minor differences, and follow similar kinetics. The vegetative cells of bacteria are significantly more susceptible to UVR than are bacterial spores or viruses. *Giardia* and *Cryptosporidium* are susceptible to practical doses of UVR and may be more sensitive because of their relatively large size.[72-74] Both large high-volume units and portable, lightweight battery-operated units are available for disinfection of small quantities of water.

Improvisational technique: UV-SODIS—UV irradiation by sunlight can substantially improve the microbiologic quality of water and reduce diarrheal illness in developing countries.[75-85] The optimal procedure for the SODIS technique is to use transparent bottles (eg, clear plastic beverage bottles), preferably lying on a dark surface and exposed to sunlight for a minimum of 4 h with intermittent agitation.[86] UV and thermal inactivation are strongly synergistic for the solar disinfection of drinking water.[67,87,88]

Assessment of supporting evidence:

- UV light is an effective means of water disinfection. **Evidence grade: 1A**
- Full sunlight exposure of clear water in a clear plastic bottle for at least 4 h significantly reduces and possibly eliminates microorganism contamination (**Evidence grade: 1B**); however, studies evaluating this technique for reduction of childhood diarrhea show mixed results. **Evidence grade: 2B**

FILTRATION

Filters are appealing because of their simplicity and suitability for commercial production. Portable water treatment products are the third highest intended purchase of outdoor equipment, after backpacks and tents.[89] Filtration is a standard step in municipal water treatment and widely used in the food and beverage industry and in many other industrial processes. Many different types of media, from sand to vegetable products to fabric have been used for water filtration throughout history in various parts of the world.[90] Filters have the advantages of being simple and requiring no holding time. They do not add any unpleasant taste and may improve taste and appearance of water. All filters eventually clog from suspended particulate matter (present even in clear streams), requiring cleaning or replacement of the filter. As a filter clogs, it requires increasing pressure to drive the water through it, which can force microorganisms through the filter or damage the filter. A crack or eroded channel in a filter will allow passage of unfiltered water. Bacteria can grow on filter media and potentially result in some bacteria in filtered water, but pathogenic bacteria and illness have not been demonstrated.[91] Silver is often incorporated into the filter media to prevent this growth, but it is not totally effective.

The primary determinant of a microorganism’s susceptibility to filtration is its size (Table 3; Figure 1). Portable filters for water treatment can be divided into microfilters with pore sizes down to 0.1 µm, ultrafilters that can remove particles as small as 0.01 µm, nanofilters with pore sizes as small as 0.001 µm or less, and reverse osmosis filters with pore sizes of 0.0001 µm or less.[69] All filters require pressure to drive the water through the filter element. The smaller the pore size, the more pressure required. Waterborne pathogens often adhere to larger particles or clump together, making them easier to remove by physical processes. Therefore, observed reductions are often greater than expected based on their individual sizes.

Most portable filters are microfilters that can readily remove protozoan cysts and bacteria but may not remove all viruses, which are much smaller than the pore size of most field filters.[92,93] Viruses often clump together and to other larger particles or organisms, resulting in an aggregate large enough to be trapped by the filter; in addition, electrochemical attraction may cause viruses to adhere to the filter surface.[47,94,95] Through these mechanisms, mechanical filters using ceramic elements with a pore size of 0.2 µm can reduce viral loads by 2 to 3 logs (99–99.9%), but they are not adequate for complete removal of viruses.[96] Ultrafiltration membranes are required for complete microbial removal, including viruses; they can also remove colloids and some dissolved solids.[97]

Recently, hollow-fiber technology has been adapted for field use; this technology uses bundles of tube fibers whose pore size can be engineered to achieve ultrafiltration with viral removal.[98] The large surface area allows these hollow-fiber filters to have relatively high flow rates at low pressure. Small group and individual gravity or hand pump filters are available through several vendors.

Some filters on the market combine the porous filter material with other substances to help the disinfection process. This may include activated charcoal, iodine, silver, and other substances. Iodine molecules can be bound in a resin engineered into field products, but the effectiveness of the resin is highly dependent on the product design and function. Most companies have abandoned iodine resin–containing portable handpump filters due to excess iodine or viral breakthrough in the effluent. Only one drink-through bottle remains on the US market, but other products may still be available outside the United States. (GAC was discussed earlier, and silver is addressed later.)

Several factors influence the decision of which filter to buy: 1) flow volume sufficient for the number of persons relying on the filter; 2) whether the filter functional claims matches the microbiologic demands that will be put on the filter; 3) the preferred means of operation (eg, hand pump or gravity); and 4) cost.

Improvisational filtration techniques—Filtration using simple, available products, such as rice hull ash filters, crushed charcoal, sponges, and various fabrics and paper, have all been used in developing countries and in emergency situations. Typically, bacteria and viruses can be reduced by as much as 50 to 85% and larger parasites by 99%, depending on the media. The effectiveness for decreasing turbidity may be used as an indicator that a filter material will reduce microbiologic contamination.[38,99,100]

Ceramic filters are a common component in portable water pump filters, but they are also a cost-effective means of household disinfection in developing countries. Ceramic clay is widely available and very inexpensive to locally manufacture in the shape of a sink or flower pot that is set into a larger container that collects the filtered water.[101-107]

Biosand filters use a technology that has been used over centuries and is still used widely in municipal plants and at the household and community level.[108-111] Sand filters can be highly effective at removing turbidity (in 1 study, from 6.2 NTU to 0.9 NTU) and improving microbiologic quality (99% efficacy), depending on their design and operation.[112,113] Sand filters are constructed by forming layers of aggregate increasing in size from the top to the bottom. The top layer is very fine sand and the bottom layer consists of large gravel. The container needs an exit port on the bottom. The top layer forms a biolayer that is important for the function of the filter. The optimum depth of a community or household sand filter is 2 m, with diameter determined by the volume of water needed. An emergency sand filter can be made in a 20 L (5.3 gal) bucket, composed of a 10 cm (3.9 in) layer of gravel beneath a 23 cm (9.1 in) layer of sand; a layer of cotton cloth, sandwiched between 2 layers of wire mesh, separates the sand and gravel layers.[38] A sand filter also can be improvised with stacked buckets of successive filter layers with holes in the bottom to allow water passage. Many websites provide design and assembly instructions, but there are no data for comparative function.

Assessments of supporting evidence:

- Filtration is effective as a primary or adjunctive means of water treatment. **Evidence grade: 1A**
- Standard commercially available microfilters with a pore size of 0.2 microns are effective in removing protozoa and bacteria. **Evidence grade: 1A**

- Ultrafiltration with pore size of less than 0.01 is needed to completely remove pathogenic viruses.**Evidence grade: 1A**
- Filters may clog, so users should know how to clean them or consider carrying a backup method of disinfection. **Evidence grade: 1C**
- Biosand filters are a reasonable improvised technique for filtration. **Evidence grade: 1B**

CHEMICAL DISINFECTION: HALOGENS (IODINE AND CHLORINE)

Worldwide, disinfection with chemicals, chiefly chlorine, is the most commonly used method for improving and maintaining the microbiologic quality of drinking water and can be used by individuals and groups in the field.[114] The germicidal activity of chlorine and other halogens is well established and results from oxidation of essential cellular structures and enzymes.[115,116] Disinfection effectiveness is determined by characteristics of the microorganism, the disinfectant, contact time, and environmental factors. Both chlorine and iodine are widely available worldwide in multiple formulations. The most commonly available form of chlorine is hypochlorite (household bleach [5 to 8%] or concentrated swimming pool granules or tablets [70%]).

Both chlorine and iodine have been used for water disinfection for more than a century. Hypochlorite, the major chlorine disinfectant, is currently the preferred means of municipal water disinfection worldwide. Both calcium hypochlorite ($Ca[OCl]_2$) and sodium hypochlorite (NaOCl) readily dissociate in water to form hypochlorite, the active disinfectant.

Iodine is also effective in low concentrations for killing bacteria, viruses, and some protozoan cysts; in higher concentrations, it is effective against fungi and even bacterial spores. However, it is a poor algaecide. Elemental iodine (I_2) and hypoiodous acid (HOI) are the major germicides in an aqueous solution. Iodine is the only halogen that is a solid at room temperature.

Given adequate concentrations and contact times, both iodine and chlorine are effective disinfectants with similar biocidal activity under most conditions.[117] Taste preference is individual. Of the halogens, iodine reacts least readily with organic compounds and is less affected by pH, indicating that low iodine residuals should be more stable and persistent than corresponding concentrations of chlorine. Despite these advantages, because of its physiologic activity, WHO recommends iodine only for short-term emergency use.

Chlorine is still advocated by the WHO and the CDC as a mainstay of large-scale community, individual household, and emergency use.[118,119] There are extensive data on effectiveness of hypochlorite in remote settings.[69,120-122] The CDC/WHO safe water system for household disinfection in developing countries provides a dosage of 1.875 or 3.75 $mg \cdot L^{-1}$ of sodium hypochlorite with a contact time of 30 min, which is sufficient to inactivate most bacteria, viruses, and some protozoa that cause waterborne diseases.[123] Another advantage of hypochlorite is the ease of adjusting the dose for large volumes of water.[45,99]

Vegetative bacteria (nonspore forming) are very sensitive to halogens.[116,124] Viruses, including hepatitis A, have intermediate sensitivity, requiring higher concentrations or longer contact times.[125-130] Protozoan cysts are more resistant than enteric bacteria and enteric viruses but some cysts (eg, *Giardia*) can be inactivated by field doses of halogens.[131-135] *Cryptosporidium* oocysts, however, are much more resistant to halogens, and inactivation is not practical with common doses of iodine and chlorine used in field water disinfection.[136,137] Little is known about *Cyclospora*, but it is assumed to be similar to *Cryptosporidium*. Certain parasitic eggs, such as those of *Ascaris*, are also resistant, but these are not commonly spread by water. (All of these resistant cysts and eggs are susceptible to heat or filtration.) Bacterial spores, such as *Bacillus anthracis*, are relatively resistant to halogens. With chlorine, however, spores are not much more resistant than are *Giardia* cysts; furthermore, they do not normally cause waterborne enteric disease. Relative susceptibility between organisms is similar for iodine and chlorine (Table 4).

Understanding factors that influence the disinfection reaction allows flexibility with greater reassurance. The primary factors of the first-order chemical disinfection reaction are concentration and contact time.[133] To achieve microbial inactivation in aqueous solution with a chemical agent, a residual concentration must be present for a specified contact time. Lower concentrations can be used with longer contact times. In field disinfection, this can be used to minimize halogen dose and improve taste or, conversely, to minimize the required contact time.

Cold water slows chemical reactions; the reaction rate can be adjusted by longer contact times or higher concentration of disinfectant chemical. Another important factor in chemical disinfection is the presence of organic and inorganic contaminants, mainly nitrogen compounds from decomposition of organisms and their wastes, fecal matter, and urea. These contaminants react, especially with chlorine, to form compounds with little or no disinfecting ability, effectively decreasing the concentration of available halogen.[26,115] Halogen demand is the amount of halogen reacting with impurities. Residual concentration is the amount of active disinfectant remaining after demand of the water is met. Halogen demand is associated with turbidity (cloudiness).[39] Typical recommendations for field treatment double the amount of chlorine or iodine in cloudy water; however, it is preferable to use clarification techniques prior to chemical disinfection in cloudy water to improve efficacy and taste.[144,145]

Because of the difficulty of estimating halogen demand, it is prudent to use 3 to 4 $mg \cdot L^{-1}$ as a target halogen concentration range for clear surface water. Lower concentrations (eg, 2 $mg \cdot L^{-1}$) can be used for back-up treatment of questionable tap water or high-quality well water (Tables 5 and 6).

Halogen toxicity—Chlorine has no known toxicity at the concentrations used for water disinfection. Sodium hypochlorite is not carcinogenic; however, reactions of chlorine with certain organic contaminants yield chlorinated hydrocarbons, chloroform, and other trihalomethanes, which are considered to have carcinogenic potential in animal models. Nevertheless, the risk of severe illness or even death from infectious diseases if disinfection is not used far exceeds any risk from byproducts of chlorine disinfection.[146]

Despite several advantages over chlorine disinfection, iodine has not gained general acceptance because of concern for its physiologic activity. Some older data indicate that iodination of water with a low residual concentration of ≤1 to 2 $mg{\cdot}L^{-1}$ appears safe, even for long periods of time, in people with normal thyroid function.[147,148] This is not the current recommendation of major agencies. Recently, the European Union stopped the sale of iodine products used for water disinfection. The WHO did not set a guideline value for iodine in drinking water because of a paucity of data and because it is not recommended for long-term disinfection. If the typical wilderness or international traveler disinfected 3 L of water a day using 2 to 4 $mg{\cdot}L^{-1}$ of iodine, the ingested amount of iodine would be 6 to 12 $mg{\cdot}d^{-1}$, well above US Institute of Medicine recommended dietary allowance levels. Levels produced by the recommended doses of iodine tablets are even higher (16 to 32 $mg{\cdot}d^{-1}$). Therefore, the use of iodine for water disinfection should be limited to short periods of ≤ 1 mo. Individuals planning to use iodine for prolonged periods should have their thyroid examined and thyroid function tests done to ensure they are initially euthyroid. Certain groups should not use iodine for water treatment: pregnant women (because of concerns of neonatal goiter); those with known hypersensitivity to iodine; persons with a history of thyroid disease, even if controlled on medication; persons with a strong family history of thyroid disease (thyroiditis); and persons from countries with chronic iodine deficiency.[149]

Improving halogen taste—Objectionable taste and smell limit the acceptance of halogens, but taste can be improved by several means. One method is to use the minimum necessary dose with a longer contact time, as in the CDC safe water system. Another method is to use higher doses and remove the taste through chemical reduction of chlorine to chloride and iodine to iodide; these have no color or taste. The best and most readily available agent is ascorbic acid (vitamin C), available in crystalline or powder form. A small pinch in a liter, mixed after the required contact time, will usually suffice. Ascorbic acid is a common ingredient of flavored drink mixes, accounting for their effectiveness in removing the taste of halogens. GAC (see above) adsorbs organic and inorganic chemicals, including iodine and chlorine byproducts, thereby improving odor and taste—the reason for its common inclusion in field filters.

Improvisational techniques—There is no comparable substitute for proven chemical disinfectants, but there are many common substances that contain halogens. Household bleach is available in most parts of the world. The active disinfectant is sodium hypochlorite. Products for disinfection of swimming pools and spas generally contain calcium hypochlorite that provides much higher concentrations than bleach. Hypochlorite is readily released from different products formulated in liquid, powder, granules, and tablets. Iodine is also available in liquid or tablets; a common household source is tincture of iodine or similar topical disinfectants with an iodine concentration of 2 to 8%. These products also contain iodide, which has no disinfecting power but does contribute to iodine toxicity. Colorless iodine solution contains only iodide and should not be used. Povidone-iodine, a topical disinfectant commonly used in medical settings, contains active iodine bound to a neutral polymer of high molecular weight that gives the iodine greater solubility and stability. In dilute aqueous solution, povidone-iodine provides a sustained-release reservoir, releasing free iodine in a concentration of 2 to 10 $mg{\cdot}L^{-1}$.[150]

MIXED SPECIES DISINFECTANT (ELECTROLYSIS)

Passing a current through a simple brine salt solution generates free available chlorine and other mixed species disinfectants that have been shown to be effective against bacteria, viruses, *Cryptosporidium*, and bacterial spores.[151,152] The process is well described and can be used on both large and small scales. The main disinfectant effect is probably attributable to a combination of chlorine dioxide, ozone, superoxides, and hypochlorous acid, giving the resulting solution greater disinfectant ability than a simple solution of sodium hypochlorite. Small units are now available commercially that use salt, water, and a 12-volt direct current (automobile) battery to create 60 mL of a 0.75% chlorine solution over a 5-min operation cycle that will treat up to 200 L of water.

Other common substances, including hydrogen peroxide and citrus juice that have some disinfectant activity, are discussed later.

Assessments of supporting evidence:

- Halogens chlorine and iodine are an effective means of disinfecting water of bacteria, viruses, and *Giardia* in the field or household when using appropriate contact time and halogen concentration. **Evidence grade: 1A**
- Usual field concentrations of iodine and chlorine are not effective for other protozoa including *Cryptosporidium* and *Cyclospora*. **Evidence grade: 2A**
- Extended use of iodine should be weighed against risks of iodine toxicity. **Evidence grade: 1B**
- Simple techniques for improving taste of halogenated water are available for field use. **Evidence grade: 1B**
- Mixed species electrolytic disinfection techniques are effective for water disinfection of microbes that are susceptible to halogens. **Evidence grade: 1B**

MISCELLANEOUS DISINFECTANTS

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, the benefits of chlorine dioxide have been limited to large-scale applications because standard formulations must be made on-site and are associated with a risk for producing volatile gas. Newer methods enable cost-effective and portable ClO_2 generation and distribution for use in an ever-widening array of small-scale applications. ClO_2-production tablets contain 6.4% sodium chlorite as the active ingredient. After a tablet is added to water, a series of complex chemical reactions occurs, generating chlorine dioxide. Some of the intermediary chemical compounds may also have anti-microbial activity.

ClO_2 has no taste or odor in water. It is capable of inactivating most waterborne pathogens, including *Cryptosporidium parvum* oocysts.[153-155] It is at least as effective a bactericide as chlorine and far superior for virus and parasite inactivation. Several commercial point-of-use applications use ClO_2 in liquid or tablet form, but relatively few data are available on product testing these products.[137] A major disadvantage for field use of tablets is the long reaction or contact time required, with upward of 2 to 4 h needed to achieve dependable disinfection. ClO_2 does not produce a lasting residual, and water undergoing chlorine dioxide disinfection must be protected from sunlight.

Assessment of supporting evidence:

- Chlorine dioxide is a widely used and potent water disinfectant, including efficacy against the protozoan parasites *Cryptosporidium*. **Evidence grade: 1A**
- Individual use products have limited data demonstrating effective concentration and contact time. **Evidence grade: 2B**

Silver—Silver ion has bactericidal effects in low doses and some attractive features, including absence of color, taste, and odor. Scant data for disinfection of viruses and protozoan cysts indicate limited effect, even at high doses. Moreover, the concentrations are strongly affected by adsorption onto the surface of any container. Silver is physiologically active but not likely to cause a problem in concentrations found in drinking water. The EPA has not approved silver for primary water disinfection in the United States, but silver is approved as a water preservative to prevent bacterial growth in previously treated and stored water. In Europe, silver tablets are sold for field water disinfection. One rational combination product combines silver with hypochlorite for both disinfection and preservation. There is some promise in steady release products and incorporation into nanoparticles.[156]

Assessment of supporting evidence:

- Use of silver in wilderness settings should be limited to water preservation and not as a primary disinfectant. **Evidence grade: 1B**

Hydrogen peroxide—Hydrogen peroxide is a strong oxidizing agent that is widely used as a preservative in food, as a sterilant for medical and food equipment, and in many other applications. Although hydrogen peroxide can sterilize water, it is not widely used as a field water disinfectant, perhaps because high concentrations known to be effective are very caustic, and there is a lack of data for protozoal cysts and quantitative data for dilute solutions. It can be used to remove the taste of hypochlorite and in combination with other processes.[157]

Assessment of supporting evidence:

- Hydrogen peroxide in typical concentration of 3% cannot be used as a primary drinking water disinfectant, and effective concentrations are not practical for field use. **Evidence grade: 1B**

Citrus and potassium permanganate—Both citrus juice and potassium permanganate have some demonstrated antibacterial effects in an aqueous solution.[158] However, data are few and not available for effect on cysts. In municipal water disinfection, potassium permanganate is used primarily for reducing contaminants to improve taste and odor.[159] Either substance could be used in an emergency to reduce bacterial and viral contamination or as an adjunct in combination with another technique, but they cannot be recommended as a primary means of water disinfection.

Assessment of supporting evidence:

- Citrus juice and potassium permanganate have limited applications for drinking water disinfection. **Evidence grade: 1C**

Nanoparticles: solar photocatalytic disinfection—Several nanomaterials have been shown to have strong anti-microbial properties and are being evaluated for use in water disinfection and purification.[160,161] The metals are of particular interest for water disinfection applications because they can be activated by UV light to produce potent oxidizers that are excellent disinfectants for microorganisms and can break down complex organic contaminants and even most heavy metals into nontoxic forms. Titanium dioxide (TiO_2) is the most effective photocatalytic substance identified to date. Recent work demonstrated inactivation of *Cryptosporidium* by titanium dioxide.[161,162] These methods are widely used in industry, but few products have incorporated the technology into individual or small group point of use products.[163,164]

Assessment of supporting evidence:

- New technology using nanoparticles and photocatalytic disinfection is highly promising for translation into point-of-use water disinfection. **Evidence grade: 2A**

PREFERRED TECHNIQUE

The optimal water treatment technique for an individual or group will depend on the number of persons to be served, space and weight accommodations, quality of source water, personal taste preferences, and fuel availability. Because halogens are not effective for killing *Cryptosporidium* at drinking water concentrations and common microfilters are not reliable for virus removal, optimal protection for all situations may require a 2-step process of 1) filtration or C-F, followed by 2) halogenation. Heat (boiling) is effective as a 1-step process in all situations but will not improve the esthetics of the water. Table 7 summarizes effects of major water disinfection methods on categories of microorganisms. Persons living or working in communities where sanitation and water treatment are lacking are at higher risk than the average international traveler. Sobsey et al reviewed data for point-of-use methods for household disinfection in developing countries[165] (Table 8).

In disaster situations such as floods, hurricanes, and earthquakes, sanitation and water treatment facilities are frequently damaged or inundated, so household or point-of-use water disinfection is advised. Chlorine is the simplest method, similar to household water disinfection where there is no sanitation or improved water sources.[20,99,169] Cloudy water should first be clarified before using hypochlorite.

On long-distance ocean-going boats where water must be desalinated as well as disinfected during the voyage, only reverse osmosis membrane filters are adequate. Water storage also requires consideration. Iodine will work for short periods only (ie, weeks) because it is a poor algaecide. For prolonged storage, water should be chlorinated and kept in a tightly sealed container to reduce the risk of contamination. For daily use, narrow-mouthed jars or containers with water spigots prevent contamination from repeated contact with hands or utensils.[170]

Relatively few studies compare multiple techniques or devices.[28,92,96,168,171-179] For more detailed discussion of disinfection techniques and available devices, see Backer.[180] For reviews of water disinfection techniques and effectiveness and efficacy data, see the following additional references.[69,168,181,182]

Sanitation

Sanitation and water treatment are inextricably linked. Studies in developing countries have demonstrated a clear benefit of safe drinking water, hygiene, and adequate sanitation in the reduction of diarrheal illness and other infections.[183-188] The benefit is greater when all are applied together, especially with appropriate education.[24,189] Personal hygiene, particularly handwashing, prevents spread of infection from food contamination during preparation of meals.[190,191] Disinfection of dishes and utensils is accomplished by rinsing in water containing enough household bleach to achieve a distinct chlorine odor. Use of halogen solutions or potassium permanganate solutions to soak vegetables and fruits can reduce microbial contamination, especially if the surface is scrubbed to remove dirt or other particulates, but neither method reaches organisms that are embedded in surface crevices or protected by other particulate matter.[192] Travelers to remote villages, wilderness areas, and persons in disaster situations should ensure proper waste disposal to prevent additional contamination of water supplies. Human waste should be buried 20 to 30 cm (8 to 12 in) deep, at least 30 m (100 ft) from any water, and at a location from which water run-off is not likely to wash organisms into nearby water sources. Groups of 3 persons or more should dig a common latrine to avoid numerous individual potholes and inadequate disposal.

Conclusion

Wilderness and international travelers should carry an effective means of disinfecting water. It is important for disaster and medical relief workers to understand the common methods of water treatment and improvisational methods. It is not possible for travelers to judge the microbiologic quality of water, and it is prudent to assume that even tap water is nonpotable in many locations. Simple and effective field techniques to improve microbiologic water quality are available to travelers. It is important to understand the basic principles and limitations of heat, filtration, and UV and chemical disinfection and then to become familiar with at least one technique appropriate for the destination, water source, and needs of the travelers.

References

1. World Health Organization. Combating waterborne disease at the household level. Geneva, Switzerland. Available at: https://www.who.int/water_sanitation_health/publications/combating-waterborne-disease/en/; 2007. Accessed February 25, 2019.

2. Schoenen D. Role of disinfection in suppressing the spread of pathogens with drinking water: possibilities and limitations. Water Res. 2002;36(15):3874–88. [PubMed: 12369533]
3. Guyatt G, Gutterman D, Baumann MH, Addrizzo-Harris D, Hylek EM, Phillips B, et al. Grading strength of recommendations and quality of evidence in clinical guidelines: report from an american college of chest physicians task force. Chest. 2006;129(1):174–81. [PubMed: 16424429]
4. Yoder J, Roberts V, Craun GF, Hill V, Hicks LA, Alexander NT, et al. Surveillance for waterborne disease and outbreaks associated with drinking water and water not intended for drinking—United States, 2005–2006. MMWR Surveill Summ. 2008;57(9):39–62. [PubMed: 18784643]
5. Colford JM Jr, Hilton JF, Wright CC, Arnold BF, Saha S, Wade TJ, et al. The Sonoma water evaluation trial: a randomized drinking water intervention trial to reduce gastrointestinal illness in older adults. Am J Public Health. 2009;99(11):1988–95. [PubMed: 19762663]
6. Reynolds KA, Mena KD, Gerba CP. Risk of waterborne illness via drinking water in the United States. Rev Environ Contam Toxicol. 2008;192:117–58. [PubMed: 18020305]
7. McClung RP, Roth DM, Vigar M, Roberts VA, Kahler AM, Cocley LA, et al. Waterborne disease outbreaks associated with environmental and undetermined exposures to water—United States, 2013–2014. MMWR Morb Mortal Wkly Rep. 2017;66(44):1222–5. [PubMed: 29120997]
8. Derlet RW, Carlson JR. An analysis of wilderness water in Kings Canyon, Sequoia, and Yosemite national parks for coliform and pathologic bacteria. Wilderness Environ Med. 2004;15(4):238–44. [PubMed: 15636373]
9. Derlet RW, Ger KA, Richards JR, Carlson JR. Risk factors for coliform bacteria in backcountry lakes and streams in the Sierra Nevada mountains: a 5-year study. Wilderness Environ Med. 2008;19(2):82–90. [PubMed: 18513116]
10. Feng Y, Xiao L. Zoonotic potential and molecular epidemiology of *Giardia* species and giardiasis. Clin Microbiol Rev. 2011;24(1):110–40. [PubMed: 21233509]
11. WHO-UNICEF. Progress on drinking water, sanitation and hygiene: 2017 update and SDG baselines. Geneva: World Health Organization (WHO) and the United Nations Children's Fund (UNICEF). Available at: https://www.unicef.org/publications/files/Progress_on_Drinking_Water_Sanitation_and_Hygiene_2017.pdf; 2017. Accessed February 25, 2019.
12. Ngwenya N, Ncube EJ, Parsons J. Recent advances in drinking water disinfection: successes and challenges. Rev Environ Contam Toxicol. 2013;222:111–70. [PubMed: 22990947]
13. WHO-UNICEF. Progress on Sanitation and Drinking Water–2015 update and MDG assessment. Geneva: World Health Organization (WHO) and the United Nations Children's Fund (UNICEF; 2015.
14. Clasen TF, Bastable A. Faecal contamination of drinking water during collection and household storage: the need to extend protection to the point of use. J Water Health. 2003;1(3):109–15. [PubMed: 15384721]
15. Gil AI, Lanata CF, Hartinger SM, Mausezahl D, Padilla B, Ochoa TJ, et al. Fecal contamination of food, water, hands, and kitchen utensils at the household level in rural areas of Peru. J Environ Health. 2014;76(6):102–6. [PubMed: 24645420]
16. Kravitz JD, Nyaphisi M, Mandel R, Petersen E. Quantitative bacterial examination of domestic water supplies in the Lesotho Highlands: water quality, sanitation, and village health. Bull World Health Organ. 1999;77(10):829–36. [PubMed: 10593031]
17. Rai SK, Ono K, Yanagida JI, Ishiyama-Imura S, Kurokawa M, Rai CK. A large-scale study of bacterial contamination of drinking water and its public health impact in Nepal. Nepal Med Coll J. 2012;14(3):234–40. [PubMed: 24047024]
18. Haramoto E. Detection of waterborne protozoa, viruses, and bacteria in groundwater and other water samples in the Kathmandu Valley, Nepal. IOP Conference Series. Earth Environ Sci. 2018;120:1–7.
19. Wright J, Gundry S, Conroy R. Household drinking water in developing countries: a systematic review of microbiological contamination between source and point-of-use. Tropical Med Int Health. 2004;9(1):106–17.
20. Lantagne D. Sodium hypochlorite dosage for household and emergency water treatment. J Am Water Works Assoc. 2008;100(8):106–19.

21. Wang G, Doyle M. Survival of enterohemorrhagic *Escherichia coli* O157:H7 in water. J Food Prot. 1998;61(6):662–7. [PubMed: 9709245]
22. Ford TE. Microbiological safety of drinking water: United States and global perspectives. Environ Health Perspect. 1999;107(suppl 1):191–206. [PubMed: 10229718]
23. Hurst C, Clark R, Regli S. Estimating the risk of acquiring infectious disease from ingestion of water. In: Hurst C, ed. Modeling Disease Transmission and its Prevention by Disinfection. Melbourne: Cambridge University Press; 1996:99–139.
24. Sobsey M, Handzel T, Venczel L. Chlorination and safe storage of household drinking water in developing countries to reduce waterborne disease. Water Sci Technol. 2003;47(3):221–8. [PubMed: 12639033]
25. Murphy JL, Kahler AM, Nansubuga I, Nanyunja EM, Kaplan B, Jothikumar N, et al. Environmental survey of drinking water sources in Kampala, Uganda, during a typhoid fever outbreak. Appl Environ Microbiol. 2017;83(23):1–11.
26. World Health Organization. Guidelines for drinking water quality. Geneva: WHO; 2011.
27. US Environmental Protection Agency. Report to Task Force: Guide Standard and Protocol for Testing Microbiological Water Purifiers. Cincinnati: USEPA; 1987 (Revision).
28. Geldreich E, Reasoner D. Home treatment devices and water quality. In: McFeters G, ed. Drinking Water Microbiology. New York: Springer-Verlag; 1990:147–68.
29. Rosen A, Booth R. Taste and odor control. In: American Water Works Association, ed. Water Quality and Treatment: A Handbook of Public Water Supplies. New York: McGraw Hill; 1971.
30. US Environmental Protection Agency Drinking Water Health Effects Task Force. Health Effects of Drinking Water Treatment Technologies. Michigan: Lewis Publisher; 1989.
31. National Academy of Sciences Safe Drinking Water Committee. The disinfection of drinking water. In: Drinking Water and Health. 2;1980:5–139.
32. Le Chevallier M, McFeters G. Microbiology of activated carbon. In: McFeters G, ed. Drinking Water Microbiology. New York: Springer-Verlag; 1990:104–20.
33. Medema GJ, Schets FM, Teunis PF, Havelaar AH. Sedimentation of free and attached *Cryptosporidium* oocysts and *Giardia* cysts in water. Appl Environ Microbiol. 1998;64(11):4460–6. [PubMed: 9797307]
34. AWWA Coagulation Committee. Committee report: coagulation as an integrated water treatment process. J Am Water Works Assoc. 1989:74.
35. Cohen J, Hannah S. Water Quality and Treatment: A Handbook of Public Water Supplies. New York: McGraw-Hill; 1971.
36. Crump JA, Okoth GO, Slutsker L, Ogaja DO, Keswick BH, Luby SP. Effect of point-of-use disinfection, flocculation and combined flocculation-disinfection on drinking water quality in western Kenya. J Appl Microbiol. 2004;97(1):225–31. [PubMed: 15186460]
37. Preston K, Lantagne D, Kotlarz N, Jellison K. Turbidity and chlorine demand reduction using alum and moringa flocculation before household chlorination in developing countries. J Water Health. 2010;8(1):60–70. [PubMed: 20009248]
38. Kotlarz N, Lantagne D, Preston K, Jellison K. Turbidity and chlorine demand reduction using locally available physical water clarification mechanisms before household chlorination in developing countries. J Water Health. 2009;7(3):497–506. [PubMed: 19491500]
39. LeChevallier MW, Evans T, Seidler RJ. Effect of turbidity on chlorination efficiency and bacterial persistence in drinking water. Appl Environ Microbiol. 1981;42(1):159–67. [PubMed: 7259162]
40. Crump JA, Otieno PO, Slutsker L, Keswick BH, Rosen DH, Hoekstra ROM, et al. Household based treatment of drinking water with flocculant-disinfectant for preventing diarrhoea in areas with turbid source water in rural western Kenya: cluster randomised controlled trial. BMJ. 2005;331(7515):478–84. [PubMed: 16046440]
41. Reller ME, Mendoza CE, Lopez MB, Alvarez M, Hoekstera RM, Olson CA, et al. A randomized controlled trial of household-based flocculant-disinfectant drinking water treatment for diarrhea prevention in rural Guatemala. Am J Trop Med Hyg. 2003;69(4):411–9. [PubMed: 14640502]
42. Powers E. Efficacy of flocculating and other emergency water purification tablets. In: Report Natick/TR-93/033. Natick, MA: United States Army Natick Research, Development and Engineering Center; 1993.

43. Powers E, Boutros C, Harper B. Biocidal efficacy of a flocculating emergency water purification tablet. Appl Environ Microbiol. 1994;60:2316–23. [PubMed: 16349318]

44. Islam MS, Ansaruzzaman M, Mahmud ZH, Marin MA, Malik AK, Neogi SB, et al. A novel and simple mixture as point-of-use water treatment agent to produce safe drinking water. Trans R Soc Trop Med Hyg. 2014;108(5):290–6. [PubMed: 24619586]

45. US Army. Sanitary control and surveillance of field water supplies. In: Dept. of Army Technical Bulletin (TB Med 577). Washington, DC: Departments of the Army, Navy, and Air Force; 2005. Available at: https://armypubs.army.mil/epubs/DR_pubs/DR_a/pdf/web/tbmed577.pdf. Accessed February 25, 2019.

46. Chaudhuri M, Sattar S. Domestic water treatment for developing countries. In: McFeters G, ed. Drinking Water Microbiology. New York: Springer-Verlag; 1990.

47. Sobsey M. Managing water in the home: accelerated health gains from improved water supply. Geneva: WHO/SDE/WSH/02.07; 2002. Available at: https://www.who.int/water_sanitation_health/dwq/WSH02.07.pdf. Accessed February 25, 2019.

48. Frazier W, Westhoff D. Preservation by Use of High Temperatures. New York: McGraw-Hill; 1978.

49. Islam MF, Johnston RB. Household pasteurization of drinking-water: the chulli water-treatment system. J Health Popul Nutr. 2006;24(3):356–62. [PubMed: 17366777]

50. Fayer R. Effect of high temperature on infectivity of *Cryptosporidium parvum* oocysts in water. Appl Environ Microbiol. 1994;60(8):273–5.

51. Bandres J, Mathewson J, DuPont H. Heat susceptibility of bacterial enteropathogens. Arch Intern Med. 1988;148(10):2261–3. [PubMed: 3052347]

52. Alder V, Simpson R. Sterilization and disinfection by heat methods. In: Russel A, Hugo W, Ayliffe G, eds. Principles and Practice of Disinfection, Preservation, and Sterilization. 2nd ed. Oxford: Blackwell Scientific; 1992:483.

53. Aukerman R, Monzingo D. Water treatment to inactive Giardia. J Forestry. 1989;87(11):18–21.

54. Ongerth J, Johnson R, MacDonald S, Frost F, Stibbs H. Backcountry water treatment to prevent giardiasis. Am J Public Health. 1989;79:1633–7. [PubMed: 2817191]

55. Bingham A, Jarroll E, EA M. Physical factors of excystation in vitro and excystation vs eosin exclusion as determinants of viability. Exp Parasitol. 1979;47(2):284–91. [PubMed: 35362]

56. Anderson B. Moist heat inactivation of *Cryptosporidium*. Am J Public Health. 1985;75:1433–4. [PubMed: 4061720]

57. Shephart M. Helminthological aspects of sewage treatment. In: Feachem R, McGarry M, Mara D, eds. Water, Wastes, and Health in Hot Climates. New York: John Wiley and Sons; 1977:299–310.

58. Perkins J. Thermal destruction of microorganisms: Heat inactivation of viruses. In: Thomas C, ed. Principles and Methods of Sterilization in Health Sciences. Springfield; 1969:63–94.

59. Tuladhar E, Bouwknegt M, Zwietering MH, Koopmans M, Duizer E. Thermal stability of structurally different viruses with proven or potential relevance to food safety. J Appl Microbiol. 2012;112(5):1050–7. [PubMed: 22404161]

60. Baert L, Debevere J, Uyttendaele M. The efficacy of preservation methods to inactivate foodborne viruses. Int J Food Microbiol. 2009;131(2–3):83–94. [PubMed: 19349089]

61. Bidawid S, Farber JM, Sattar SA, Hayward S. Heat inactivation of hepatitis A virus in dairy foods. J Food Prot. 2000;63(4):522–8. [PubMed: 10772219]

62. Krugman S, Giles J, Hammond J. Hepatitis virus: effect of heat on the infectivity and antigenicity of the MS-1 and MS-2 strains. J Infect Dis. 1970;122:432–6. [PubMed: 5476393]

63. World Health Organization. Boil water. Available at: http://www.who.int/water_sanitation_health/dwq/Boiling_water_01_15.pdf?ua=1; 2015. Accessed February 25, 2019.

64. Neumann H. Alternatives to water chlorination (Correspondence). Rev Infect Dis. 1981;3(6):1255–7. [PubMed: 7200632]

65. Neumann H. Bacteriological safety of hot tapwater in developing countries. Public Health Rep. 1969;84(9):812–4. [PubMed: 4979882]

66. Groh C, MacPherson D, Groves D. Effect of heat on the sterilization of artifically contaminated water. J Travel Med. 1996;3(1):11–3. [PubMed: 9815415]

67. McGuigan KG. Solar disinfection: use of sunlight to decontaminate drinking water in developing countries. J Med Microbiol. 1999;48(9):785–7. [PubMed: 10482288]

68. Ciochetti DA, Metcalf RH. Pasteurization of naturally contaminated water with solar energy. Appl Environ Microbiol. 1984;47(2):223–8. [PubMed: 6712206]

69. LeChevallier M, Kwok-Keung A. Water Treatment and Pathogen Control. London: UK. 2004.

70. Abd-Elmaksoud S, Naranjo JE, Gerba CP. Assessment of a portable handheld UV light device for the disinfection of viruses and bacteria in water. Food Environ Virol. 2013;5(2):87–90. [PubMed: 23412725]

71. Reygadas F, Gruber JS, Ray I, Nelson KL. Field efficacy evaluation and post-treatment contamination risk assessment of an ultraviolet disinfection and safe storage system. Water Res. 2015;85:74–84. [PubMed: 26302217]

72. Hijnen WA, Beerendonk EF, Medema GJ. Inactivation credit of UV radiation for viruses, bacteria and protozoan (oo)cysts in water: a review. Water Res. 2006;40(1):3–22. [PubMed: 16386286]

73. Linden KG, Shin GA, Faubert G, Cairns W, Sobsey MD. UV disinfection of *Giardia lamblia* cysts in water. Environ Sci Technol. 2002;36(11):2519–22. [PubMed: 12075814]

74. Zimmer JL, Slawson RM, Huck PM. Inactivation and potential repair of *Cryptosporidium* parvum following low- and medium-pressure ultraviolet irradiation. Water Res. 2003;37(14):3517–23. [PubMed: 12834745]

75. McGuigan KG, Conroy RM, Mosler HJ, Preez du M, Ubomba-Jaswa E, Fernandez-Ibañez P. Solar water disinfection (SODIS): a review from bench-top to roof-top. J Hazard Mater. 2012;235–236:29–46.

76. Berney M, Weilenmann HU, Simonetti A, Egli T. Efficacy of solar disinfection of *Escherichia coli*, *Shigella flexneri*, *Salmonella typhimurium* and *Vibrio cholerae*. J Appl Microbiol. 2006;101(4):828–36. [PubMed: 16968294]

77. Cervantes DXF. Feasibility of semi-continuous solar disinfection system for developing countries at the household level. Massachusetts Institute of Technology; 2003. Available at: http://hdl.handle.net/1721.1/29551. Accessed February 25, 2019.

78. Joyce T, McGuigan K, Elmore-Meegan M, Conroy R. Inactivation of fecal bacteria in drinking water by solar heating. Appl Environ Microbiol. 1996;62(2):399–402. [PubMed: 8593045]

79. Conroy RM, Meegan ME, Joyce T, McGuigan K, Barnes J. Solar disinfection of drinking water protects against cholera in children under 6 years of age. Arch Dis Child. 2001;85(4):293–5. [PubMed: 11567937]

80. King BJ, Hoefel D, Daminato DP, Fanok S, Monis PT. Solar UV reduces *Cryptosporidium parvum* oocyst infectivity in environmental waters. J Appl Microbiol. 2008;104(5):1311–23. [PubMed: 18248370]

81. Tedeschi C, Barsi C, Peterson S, Carey K. A pilot study of solar water disinfection in the wilderness setting. J Wild Environ Med. 2014;25(3):340–5.

82. Mausezahl D, Christen A, Pacheco GD, Tellez FA, Inarte M, Zapata ME, et al. Solar drinking water disinfection (SODIS) to reduce childhood diarrhoea in rural Bolivia: a cluster-randomized, controlled trial. PLoS Med. 2009;6(8), e1000125. [PubMed: 19688036]

83. Du Preez M, McGuigan KG, Conroy RM. Solar disinfection of drinking water in the prevention of dysentery in South African children aged under 5 years: the role of participant motivation. Environ Sci Technol. 2010;44(22):8744–9. [PubMed: 20977257]

84. du Preez M, Conroy RM, Ligondo S, Hennessy J, Elmore-Meegan M, Soita A, et al. Randomized intervention study of solar disinfection of drinking water in the prevention of dysentery in Kenyan children aged under 5 years. Environ Sci Technol. 2011;45(21):9315–23. [PubMed: 21936492]

85. Conroy RM, Elmore-Meegan M, Joyce T, McGuigan KG, Barnes J. Solar disinfection of drinking water and diarrhoea in Maasai children: a controlled field trial. Lancet (Lond Engl). 1996;348(9043):1695–7.

86. Meierhofer R, Wegelin M. SODIS Manual. Gallen: department of water and sanitation in developing countries, Swiss federal institute of envirnomental science and technology; 2002. Available at: https://www.sodis.ch/methode/anwendung/ausbildungsmaterial/dokumente_material/sodismanual_2016.pdf. Accessed February 25, 2019.

87. McGuigan K, Joyce T, Conroy R, Gillespie J, Elmore-Meegan M. Solar disinfection of drinking water contained in transparent plastic bottles: characterizing the bacterial inactivation process. J Appl Microbiol. 1998;84(6):1138–48. [PubMed: 9717300]

88. Rijal GK, Fujioka RS. Synergistic effect of solar radiation and solar heating to disinfect drinking water sources. Water Sci Technol. 2001;43(12):155–62.

89. Jenkins M. What's in the water?. In: Backpacker. 1996:56.

90. Larson KL, Hansen C, Ritz M, Carreno D. Acceptance and impact of point-of-use water filtration systems in rural Guatemala. JNurs Scholarsh. 2017;49(1):96–102. [PubMed: 27802369]

91. Zhang Y, Wang Q, Lou W, Wang Y, Zhu X. Microbiological safety of household membrane water filter. J Environ Biol. 2013;34(2 Spec No):481–7. [PubMed: 24620621]

92. Environmental Health Directorate Health Protection Branch. Assessing the Effectiveness of Small Filtration Systems for Point-of-Use Disinfection of Drinking Water Supplies. Ottawa: Department of National Health and Welfare; 1980, 80-EHD-54.

93. Schlosser O, Robert C, Bourderioux C, Rey M, de Roubin MR. Bacterial removal from inexpensive portable water treatment systems for travelers. J Travel Med. 2001;8(1):12–8. [PubMed: 11182604]

94. Clasen T, Brown J, Suntura O, Collin S. Safe household water treatment and storage using ceramic drip filters: a randomised controlled trial in Bolivia. Water Sci Technol. 2004;50(1):111–5.

95. Rao V, Symons JM, Ling A, Wang P, Metcalf TG, Hoff JC, et al. Removal of hepatitis A virus and rotavirus by drinking water treatment. J Am Water Works Assoc. 1988;80(2):59–67.

96. Horman A, Rimhanen-Finne R, Maunula L, von Bonsdorff CH, Rapala J, Lahti K, et al. Evaluation of the purification capacity of nine portable, small-scale water purification devices. Water Sci Technol. 2004;50(1):179–83.

97. Mull B, Hill VR. Recovery of diverse microbes in high turbidity surface water samples using dead-end ultrafiltration. J Microbiol Methods. 2012;91(3):429–33. [PubMed: 23064261]

98. Lindquist ED, George CM, Perin J, Neiswender de Calari K, Norman WR, Davis TP, et al. A cluster randomized controlled trial to reduce childhood diarrhea using hollow fiber water filter and/or hygiene-sanitation educational interventions. Am J Trop Med Hyg. 2014;91(1):190–7. [PubMed: 24865680]

99. Lantagne D, Person B, Smith N, Mayer A, Preston K, Blanton E, et al. Emergency water treatment with bleach in the United States: the need to revise EPA recommendations. Environ Sci Technol. 2014;48(9):5093–100. [PubMed: 24684410]

100. Kozlicic A, Hadzic A, Bevanda H. Improvised purification methods for obtaining individual drinking water supply under war and extreme shortage conditions. Prehosp Disaster Med. 1994;9(2 Suppl):S25–8. [PubMed: 10155514]

101. Morris JF, Murphy J, Fagerli K, Schneeberger C, Jarohn P, Moke F, et al. A randomized controlled trial to assess the impact of ceramic water filters on prevention of diarrhea and Cryptosporidiosis in infants and young children-Western Kenya, 2013. Am J Trop Med Hyg. 2018;98(5):1260–8. [PubMed: 29611500]

102. Moropeng RC, Budeli P, Mpenyana-Monyatsi L, Momba MNB. Dramatic reduction in diarrhoeal diseases through implementation of cost-effective household drinking water treatment systems in Makwane Village, Limpopo Province, South Africa. Int J Environ Res Public Health. 2018;15(3):410. [PubMed: 29495483]

103. Kirby MA, Nagel CL, Rosa G, Umupfasoni MM, Iyakeremye L, Thomas EA, et al. Use, microbiological effectiveness and health impact of a household water filter intervention in rural Rwanda - a matched cohort study. Int J Hyg Environ Health. 2017;220(6):1020–9. [PubMed: 28596086]

104. du Preez M, Conroy RM, Wright JA, Moyo S, Potgieter N, Gundry SW. Use of ceramic water filtration in the prevention of diarrheal disease: a randomized controlled trial in rural South Africa and Zimbabwe. Am J Trop Med Hyg. 2008;79(5):696–701. [PubMed: 18981506]

105. Clasen TF, Brown J, Collin S, Suntura O, Cairncross S. Reducing diarrhea through the use of household-based ceramic water filters: a randomized, controlled trial in rural Bolivia. Am J Trop Med Hyg. 2004;70(6):651–7. [PubMed: 15211008]

106. Clasen T, Garcia Parra G, Boisson S, Collin S. Household-based ceramic water filters for the prevention of diarrhea: a randomized, controlled trial of a pilot program in Colombia. Am J Trop Med Hyg. 2005;73(4):790–5. [PubMed: 16222027]

107. Brown J, Sobsey MD, Loomis D. Local drinking water filters reduce diarrheal disease in Cambodia: a randomized, controlled trial of the ceramic water purifier. Am J Trop MedHyg. 2008;79(3):394–400.

108. Tiwari SS, Schmidt WP, Darby J, Kariuki ZG, Jenkins MW. Intermittent slow sand filtration for preventing diarrhoea among children in Kenyan households using unimproved water sources: randomized controlled trial. Tropical Med Int Health. 2009;14(11):1374–82.

109. Stauber CE, Ortiz GM, Loomis DP, Sobsey MD. A randomized controlled trial of the concrete biosand filter and its impact on diarrheal disease in Bonao, Dominican Republic. Am J Trop Med Hyg. 2009;80(2):286–93. [PubMed: 19190228]

110. Stauber CE, Kominek B, Liang KR, Osman MK, Sobsey MD. Evaluation of the impact of the plastic BioSand filter on health and drinking water quality in rural Tamale, Ghana. Int J Environ Res Public Health. 2012;9(11):3806–33. [PubMed: 23202818]

111. Fabiszewski de Aceituno AM, Stauber CE, Walters AR, Meza Sanchez RE, Sobsey MD. A randomized controlled trial of the plastic-housing BioSand filter and its impact on diarrheal disease in Copan, Honduras. Am J Trop Med Hyg. 2012;86(6):913–91. [PubMed: 22665593]

112. Duke WF, Nordin RN, Baker D, Mazumder A. The use and performance of BioSand filters in the Artibonite Valley of Haiti: a field study of 107 households. Rural Remote Health. 2006;6(3):570. [PubMed: 16889468]

113. Regli S. Regulations on filtration and disinfection. Conference on current research in drinking water treatment. 1987. Cincinnati, OH.

114. Fagerli K, Trivedi KK, Sodha SV, Blanton E, Ati A, Nguyen T, et al. Comparison of boiling and chlorination on the quality of stored drinking water and childhood diarrhoea in Indonesian households. Epidemiol Infect. 2017;145(15):3294–302. [PubMed: 28942755]

115. World Health Organization. Water Treatment and Pathogen Control: Process Efficiency in Achieving Safe Drinking Water. London, UK: World Health Organization; 2004.

116. White G. Handbook of Chlorination. 3rd ed. NewYork: Van Nostrand Reinhold; 1992.

117. Jarroll E, Hoff J, Meyer E. Resistance of cysts to disinfection agents. In: Erlandsen S, Meyer E, eds. Giardia and Giardiasis: Biology, Pathogenesis and Epidemiology. New York: Plenum Press; 1984:311–28.

118. Centers for Disease Control and Prevention. Safe Water Systems for the Developing World: A Handbook for Implementing Household-Based Water Treatment and Safe Storage Projects. Atlanta, GA: Centers for Disease Control and Prevention; 2001.

119. Lantagne DS. Viability of commercially available bleach for water treatment in developing countries. Am J Public Health. 2009;99(11):1975–8. [PubMed: 19762657]

120. Arnold BF, Colford JM Jr. Treating water with chlorine at point-of-use to improve water quality and reduce child diarrhea in developing countries: a systematic review and meta-analysis. Am J Trop Med Hyg. 2007;76(2):354–64. [PubMed: 17297049]

121. Pickard B, Clarke S, Bettin W. Chlorine disinfection in the use of individual water purification devices. US Army Center for Health Promotion and Preventive Medicine (USACHPPM); 2006. Available at: https://apps.dtic.mil/dtic/tr/fulltext/u2/a454058.pdf. Accessed February 26, 2019.

122. Mengistie B, Berhane Y, Worku A. Household water chlorination reduces incidence of diarrhea among under-five children in rural Ethiopia: a cluster randomized controlled trial. PLoS One. 2013;8(10), e77887. [PubMed: 24194899]

123. Shrestha RK, Marseille E, Kahn JG, Lule JR, Pitter C, Blandford JM, et al. Cost-effectiveness of home-based chlorination and safe water storage in reducing diarrhea among HIV-affected households in rural Uganda. Am J Trop Med Hyg. 2006;74(5):884–90. [PubMed: 16687697]

124. Blaser M. Inactivation of *Campylobacter jejuni* by chlorine and monochlorine. Appl Environ Microbiol. 1986;51(2):307–11. [PubMed: 3954344]

125. Engelbrecht R, Weber MJ, Salter BL, Schmidt CA. Comparative inactivation of viruses by chlorine. Appl Environ Microbiol. 1980;40:249–55. [PubMed: 6258473]

126. Shin GA, Sobsey MD. Inactivation of norovirus by chlorine disinfection of water. Water Res. 2008;42(17):4562–8. [PubMed: 18760818]

127. Grabow W, Gauss-Muller V, Prozesky OW, Deinhardt F. Inactivation of hepatitis A virus and indicator organisms in water by free chlorine residuals. Appl Environ Microbiol. 1983;46(3):619–24. [PubMed: 6314894]

128. Sobsey M, Fuji T, Hall R. Inactivation of cell-associated and dispersed hepatitis A virus in water. J Am Water Works Assoc. 1991;83(11):64–7.

129. Craun G, Swedlow D, Tauxe R, Clark R, Fox K, Geldreich E, et al. Prevention of waterborne cholera in the United States. J Am Water Works Assoc. 1991;83(11):40–5.

130. Thraenhart O. Measures for disinfection and control of viral hepatitis. In: Block S, ed. Disinfection, Sterilization, and Preservation. 4th ed. Philadelphia: Lea & Febiger; 1991:445–72.

131. Fraker L, Gentile D, Krivoy D, Condon M, Backer H. *Giardia* cyst inactivation by iodine. J Wilderness Med. 1992;3(4):351–8.

132. Hibler C, Hancock C, Perger L, Wegrzyn J, Swabby K. Inactivation of Giardia Cysts with Chlorine at 0.5C to 5.0C. AWWA Research Foundation: Denver; 1987.

133. Hoff J. Inactivation of Microbial Agents by Chemical Disinfectants. Cincinnati: US Environmental Protection Agency; 1986. EPA/600/2-86/067.

134. Rubin A, Evers D, Eyman C, Jarroll E. Inactivation of Gerbil-cultured *Giardia lamblia* cysts by free chlorine. Appl Environ Microbiol. 1989;55(10):2592–4. [PubMed: 2604397]

135. Wallis P, Hammond BR. Removal and inactivation of *Giardia* cysts in a mobile water treatment plant under field condition: preliminary results. In: Wallis P, Hammond B, eds. Advances in Giardia Research. Calgary: University of Calgary Press; 1988:137–44.

136. Carpenter C, Fayer R, Trout J, Beach MJ. Chlorine disinfection of recreational water for *Cryptosporidium parvum*. Emerg Infect Dis. 1999;5(4):579–84. [PubMed: 10458969]

137. Korich DG, Mead JR, Madore MS, Sinclair NA, Sterling CR. Effects of ozone, chlorine dioxide, chlorine, and monochloramine on *Cryptosporidium parvum* oocyst viability. Appl Environ Microbiol. 1990;56(5):1423–8. [PubMed: 2339894]

138. Briton G. Introduction to Environmental Virology. New York: Wiley; 1980.

139. Chang S. Modern concepts of disinfection: water treatment in the seventies. In: Proceedings of National Specialty Conference on Disinfection. 1970.

140. Rice E, Hoff J, Schaefer F. Inactivation of *Giardia* cysts by chlorine. Appl Environ Microbiol. 1982;43:250–1. [PubMed: 7055375]

141. Shields J, Hill V, Arrowood M, Beach M. Inactivation of *Cryptosporidium parvum* under chlorinated recreational water conditions. J Water Health. 2018;6(4):513–20.

142. Sobsey M, Oldham C, McCall D. Comparative inactivation of hepatitis A and other enteroviruses in water by iodine. Water Sci Technol. 1991;24(2):331–7.

143. Berg G, Chang S, Harris E. Devitalization of microorganisms by iodine. Virology. 1964;22:469–81.

144. Gerba C, Johnson D, Hasan M. Efficacy of iodine water purification tablets against *Cryptosporidium* oocysts and *Giardia* cysts. Wilderness Environ Med. 1997;8(2):96–100. [PubMed: 11990150]

145. Mohamed H, Brown J, Njee RM, Clasen T, Malebo HM, Mbuligwe S. Point-of-use chlorination of turbid water: results from a field study in Tanzania. J Water Health. 2015;13(2):544–52. [PubMed: 26042985]

146. Lantagne DS, Cardinali F, Blount BC. Disinfection by-product formation and mitigation strategies in point-of-use chlorination with sodium dichloroisocyanurate in Tanzania. Am J Trop Med Hyg. 2010;83(1):135–43. [PubMed: 20595492]

147. Kinman R, Black A, Thomas W. Disinfection with iodine. In: Water Treatment in the Seventies: Procedings of national specialty conference on disinfection. 1970.

148. Thomas W, Black A, Freund G, Kinman R. Iodine disinfection of water. Arch Environ Health. 1969;19(1):124–32. [PubMed: 4182160]

149. Backer H, Hollowell J. Use of iodine for water disinfection: iodine toxicity and maximum recommended dose. Environ Health Perspect. 2000;108(8):679–84. [PubMed: 10964787]

150. Gottardi W. Iodine and iodine compounds. In: Block S, ed. Disinfection, Sterilization, and Preservation. 4th ed. Philadelphia: Lea & Febiger; 1991:152–67.

151. Rutala WA, Weber DJ. New disinfection and sterilization methods. Emerg Infect Dis. 2001;7(2):348–53. [PubMed: 11294738]

152. Venczel L, Arrowood M, Hurd M, Sobsey M. Inactivation of *Cryptosporidium parvum* oocysts and *Clostridium perfringens* spores by a mixed-oxidant disinfectant and by free chlorine. Appl Environ Microbiol. 1997;63(4):1598–601. [PubMed: 9097455]

153. Clark RM, Sivagnesan M, Rice EW, Chen J. Development of a Ct equation for the inactivation of *Cryptosporidium* occysts with chlorine dioxide. Water Res. 2003;37(11):2773–83. [PubMed: 12753856]

154. Murphy JL, Haas CN, Arrowood MJ, Hlavsa MC, Beach MJ, Hill VR. Efficacy of chlorine dioxide tablets on inactivation of cryptosporidium oocysts. Environ Sci Technol. 2014;48(10):5849–56. [PubMed: 24797292]

155. Pereira JT, Costa AO, de Oliveira Silva MB, Schuchard W, Osaki SC, de Castro EA, et al. Comparing the efficacy of chlorine, chlorine dioxide, and ozone in the inactivation of *Cryptosporidium parvum* in water from Parana State, Southern Brazil. Appl Biochem Biotechnol. 2008;151(2–3):464–73. [PubMed: 18498060]

156. Marchin G. Fina L Contact and demand-release disinfectants. Crit Rev Environ Control. 1989;19:227–90.

157. Fisher MB, Keenan CR, Nelson KL, Voelker BM. Speeding up solar disinfection (SODIS): effects of hydrogen peroxide, temperature, pH, and copper plus ascorbate on the photoinactivation of *E. coli*. J Water Health. 2008;6(1):35–51. [PubMed: 17998606]

158. D'Aquino M, Teves SA. Lemon juice as a natural biocide for disinfecting drinking water. Bull Pan Am Health Organ. 1994;28(4):324–30. [PubMed: 7858646]

159. United States Environmental Protection Agency. Alternative Disinfectants and Oxidants Guidance Manual. In: EPA 815-R-99-014. US EPA; 1999. Available at: https://nepis.epa.gov. Accessed February 26, 2019.

160. Chong MN, Jin B, Chow CW, Saint C. Recent developments in photocatalytic water treatment technology: a review. Water Res. 2010;44(10):2997–3027. [PubMed: 20378145]

161. Li Q, Mahendra S, Lyon DY, Brunet L, Liga MV, Li D, et al. Antimicrobial nanomaterials for water disinfection and microbial control: potential applications and implications. Water Res. 2008;42(18):4591–602. [PubMed: 18804836]

162. Sunnotel O, Verdoold R, Dunlop PS, Snelling WJ, Lowery CJ, Dooley JS, et al. Photocatalytic inactivation of *Cryptosporidium parvum* on nanostructured titanium dioxide films. J Water Health. 2010;8(1):83–91. [PubMed: 20009250]

163. Blanco-Galvez J, Fernandez-Ibanez P, Malato-Rodriguez S. Solar photocatalytic detoxification and disinfection of water: recent overview. J Solar Energy Eng. 2006;129(1):4–15.

164. Alrousan DM, Dunlop PS, McMurray TA, Byrne JA. Photocatalytic inactivation of *E. coli* in surface water using immobilised nanoparticle TiO2 films. Water Res. 2009;43(1):47–54. [PubMed: 19007965]

165. Sobsey MD, Stauber CE, Casanova LM, Brown JM, Elliott MA. Point of use household drinking water filtration: a practical, effective solution for providing sustained access to safe drinking water in the developing world. Environ Sci Technol. 2008;42(12):4261–7. [PubMed: 18605542]

166. Bielefeldt AR, Kowalski K, Summers RS. Bacterial treatment effectiveness of point-of-use ceramic water filters. Water Res. 2009;43(14):3559–65. [PubMed: 19500815]

167. Mwabi JK, Mamba BB, Momba MN. Removal of *Escherichia coli* and faecal coliforms from surface water and groundwater by household water treatment devices/systems: a sustainable solution for improving water quality in rural communities of the Southern African development community region. Int J Environ Res Public Health. 2012;9(1):139–70. [PubMed: 22470284]

168. Clasen T, Menon S. Microbiological performance of common water treatment devices for household use in India. Int J Environ Health Res. 2007;17(2):83–93. [PubMed: 17616864]

169. Brunkard JM, Ailes E, Roberts VA, Hill V, Hilborn ED, Craun GF, et al. Surveillance for waterborne disease outbreaks associated with drinking water—United States, 2007–2008. MMWR Surveill Summ. 2011;60(12):38–68. [PubMed: 21937977]

170. Sobel J, Mahon B, Mendoza C, Passaro D, Cano F, Baier K, et al. Reduction of fecal contamination of street-vended beverages in Guatemala by a simple system for water purification and storage, handwashing, and beverage storage. Am J Trop Med Hyg. 1998;59(3):380–7. [PubMed: 9749629]

171. Cullimore D, Jacobsen H. The efficiency of point of use devices for the exclusion of *Giardia muris* cysts from a model water supply system. In: Wallis P, Hammond B, eds. Advances in Giardia Research. Calgary: University of Calgary Press; 1988:107–12.

172. Hutton P, Ongerth J. Performance evaluation for portable water treatment filters. Seattle, WA: Department of Environmental Health, University of Washington; 1995.

173. Hutton P, Ongerth J. Performance evaluation of ten commercially available portable water filters. Sydney, Austalia: Department of Water Engineering, University of New South Wales; 1997.

174. Jarroll E, Bingham A, Meyer E. *Giardia* cyst destruction: effectiveness of six small water disinfection methods. Am J Trop Med Hyg. 1980;29(1):8–11. [PubMed: 7352632]

175. Logsdon G, Symons J, Hoye R, Arozarena M. Alternative filtration methods for removal of *Giardia* cysts and cyst models. J Am Water Works Assoc. 1981;73(2):111–8.

176. Naranjo J, Gerba C. Evaluation of portable water treatment devices by a condensed version of the guide of standard protocol for microbiological purifiers (USEPA, 1987). Tucson, AZ: University of Arizona; 1995.

177. Powers E, Boyd C, Harper B, Rubin A. Removal of biological and chemical challenge from water by commercial fresh and salt water purification devices. In: Technical Report Natick/TR-91-042. Natick, MA: United States Army Natick Research, Development and Engineering Center; 1991.

178. Tobin R. Performance of point-of-use water treatment devices. In: Proceedings of the first conference on cold regions environmental engineering. 1983. Fairbanks, AK.

179. Tobin R. Testing and evaluating point-of-use treatment devices in Canada. J Am Water Works Assoc. 1987;79(10):42–5.

180. Backer H. Field water disinfection. In: Auerbach P, ed. Wilderness Medicine. 7th ed. Philadelphia: Elsevier; 2017.

181. McDonnell GE. Antisepsis, Disinfection, and Sterilization. Washington, DC: ASM Press; 2007.

182. Bielefeldt AR. Appropriate and sustainable water disinfection methods for developing communities. In: Buchanan K, ed. Water Disinfection. New York City, NY: Nova Science Publishers; 2011:45–75.

183. Clasen T, Roberts I, Rabie T, Schmidt W, Cairncross S. Interventions to improve water quality for preventing diarrhoea. Cochrane Library: John Wiley & Sons; 2006.

184. Opryszko MC, Majeed SW, Hansen PM, Myers JA, Baba D, Thompson RE, et al. Water and hygiene interventions to reduce diarrhoea in rural Afghanistan: a randomized controlled study. J Water Health. 2010;8(4):687–702. [PubMed: 20705980]

185. Jung S, Doh YA, Bizuneh DB, Beyene H, Seong J, Kwon H, et al. The effects of improved sanitation on diarrheal prevalence, incidence, and duration in children under five in the SNNPR State, Ethiopia: study protocol for a randomized controlled trial. Trials. 2016;17(1):204. [PubMed: 27089872]

186. Garrett V, Ogutu P, Mabonga P, Ombeki S, Mwaki A, Aluoch G, et al. Diarrhoea prevention in a high-risk rural Kenyan population through point-of-use chlorination, safe water storage, sanitation, and rainwater harvesting. Epidemiol Infect. 2008;136(11):1463–71. [PubMed: 18205977]

187. Dreibelbis R, Freeman MC, Greene LE, Saboori S, Rheingans R. The impact of school water, sanitation, and hygiene interventions on the health of younger siblings of pupils: a cluster-randomized trial in Kenya. Am J Public Health. 2014;104(1):e91–7.

188. Cha S, Lee J, Seo D, Park BM, Mansiangi P, Mernard K, et al. Effects of improved sanitation on diarrheal reduction for children under five in Idiofa, DR Congo: a cluster randomized trial. Infect Dis Poverty. 2017;6(1):137–49. [PubMed: 28923093]

189. Quick RE, Kimura A, Thevos A, Tembo M, Shamputa I, Hutwagner L, et al. Diarrhea prevention through household-level water disinfection and safe storage in Zambia. Am J Trop Med Hyg. 2002;66(5):584–9. [PubMed: 12201595]

190. Luby SP, Agboatwalla M, Painter J, Altaf A, Billhimer WL, Hoekstra RM, et al. Effect of intensive handwashing promotion on childhood diarrhea in high-risk communities in Pakistan: a randomized controlled trial. JAMA. 2004;291(21):2547–54. [PubMed: 15173145]

191. Hashi A, Kumie A, Gasana J. Hand washing with soap and WASH educational intervention reduces under-five childhood diarrhoea incidence in Jigjiga District, Eastern Ethiopia: a community-based cluster randomized controlled trial. Prev Med Rep. 2017;6:361–8. [PubMed: 28507890]

192. Ortega YR, Roxas CR, Gilman RH, Miller NJ, Cabrera L, Taquiri C, et al. Isolation of *Cryptosporidium parvum* and *Cyclospora cayetanensis* from vegetables collected in markets of an endemic region in Peru. Am J Trop Med Hyg. 1997;57(6):683–6. [PubMed: 9430527]

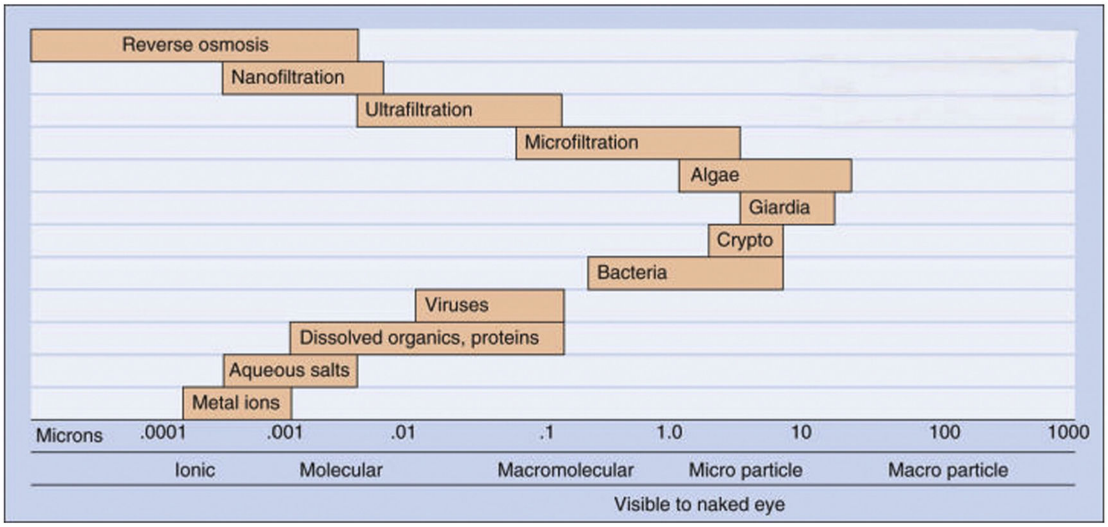

Figure 1. Levels of filtration and susceptibility of common microbial pathogens and other contaminants.

Adapted from Backer H. Water disinfection for international travelers. In: Keystone JS, Kozarsky PE, Connor BA, eds. *Travel Medicine*. 4th ed. Philadelphia, PA: Elsevier; 2019:31–41. Copyright 2019, reprinted with permission from Elsevier.

Table 1.

Heat inactivation of microorganisms

Organism	Lethal temperature/Time	Reference
Protozoan cysts, including *Giardia, Entamoeba histolytica*	50°C (122°F) for 10 min 55°C (131°F) for 5 min 100°C (212°F) immediately	[53-55]
Cryptosporidium oocysts	55°C (131°F) warmed over 20 min 64°C (148°F) within 2 min	[50,56]
Parasitic eggs, larvae, and cercariae	50°C–55°C (122–131°F)	[57]
Common bacterial enteric pathogens (*E coli*, *Salmonella*, *Campylobacter*, *Shigella*)	55°C (131°F) for 30 min or 65°C (149°F) for less than 1 min (standard pasteurization temperatures)	[48,51]
Viruses	56°C–60°C (133–140°F) in less than 20–40 min	[52,58,59]
Hepatitis A virus	98°C (208°F) for 1 min 75°C (167°F) for less than 0.5 min 85°C (185°F) for 1 min or less (in various food products)	[60-62]

Table 2.

Boiling temperatures at various altitudes

Altitude (ft)	**Altitude (m)**	**Boiling point**
5000	1524	95° C (203°F)
10,000	3048	90° C (194°F)
14,000	4267	86°C (187°F)
19,000	5791	81°C (178°F)

Table 3.

Microorganism susceptibility to filtration

Organism	***Approximate size (μm)***	***Recommended filter rating (μm)***
Viruses[a]	0.03	Ultrafilter, nanofilter, reverse osmosis
Escherichia coli	0.5 by 3–8	0.2–0.4 (microfilter)
Campylobacter	0.2–0.4 by 1.5–3.5	
V cholerae	0.5 by 1.5–3.0	
Cryptosporidium oocyst	2–6	1 (microfilter)
Giardia cyst	6–10 by 8–15	3–5 (microfilter)
Entamoeba histolytica cyst	5–30 (average 10)	
Nematode eggs	30–40 by 50–80	20 (microfilter)
Schistosome cercariae	50 by 100	Coffee filter or fine cloth, or double thickness
Dracunculus larvae	20 by 500	closely woven cloth

[a] Microfilters (includes most filters with pore size of 0.1–0.2 μm) can filter bacteria and protozoan cysts, but are not effective for virus removal unless designed to rely on electrostatic trapping of viruses. Hollow fiber filters with 0.02 μm pores and reverse osmosis filters are capable of filtering viruses.

Table 4.

Disinfection data for chlorine and iodine to achieve 99.9% kill or inactivation[a] of select microorganisms

Organism	Concentration (mg·L^{-1})	Time (min)	pH	Temp	Disinfection constant (Ct)[a]	Reference
Chlorine						
Escherichia coli	0.1	0.16	6.0	5°C (41°F)	0.016	116
Campylobacter	0.3	0.5	6.0–8.0	25° C (77°F)	0.15	124
20 enteric virus	0.5	60	7.8	2°C (36°F)	30	138
6 enteric viruses	0.5	4.5	6.0–8.0	5°C (41°F)	2.5	125
Norovirus	1	10	6.0	5°C	10	126
	5	20 sec			1.66	
Hepatitis A virus	0.5	1	6.0	25° C (77°F)	0.5	127
Amebic cysts	3.5	10		25° C (77°F)	35	139
Giardia cysts	2.5	60	6.0–8.0	5°C (41°F)	150	140
Giardia lamblia cysts	0.85	90	8.0	2–3°C (36–37°F)	77	135
Giardia muris cysts	3.05	50	7.0	5°C (41°F)	153	134
Cryptosporidium (2 strains)	20	755	7.5	23°C	15,300	141
	20	501	7.5	23°C	10,400	
Iodine						
Escherichia coli	1.3	1	6.0–7.0	2–5°C (36–41°F)	1.3	31
Hepatitis A‡	8	.4	7.0	25°C	3	142
Coxsackie virus	0.5	30	7.0	5°C (41°F)	15	143
Amebic cysts	3.5	10		25° C (77°F)	35	139
Giardia cysts	4	15	5.0	30°C (86°F)	60[b]	131
Giardia cysts	4	45	5.0	15°C (59°F)	170[b]	131
Giardia cysts	4	120	5.0	5°C (41°F)	480[b]	131

[a] 99.9% is for comparison of disinfection potency and microorganism susceptibility. The standard for potable water is 99.99% kill for viruses and 99.999% for bacteria. This would be achieved in each example with a higher concentration of disinfectant or a longer contact time.

[b] 100% kill; viability tested only at 15, 30, 45, 60, and 120 min.

Table 5.

Halogen disinfection products and recommended doses

Iodination techniques[a]	**Add to 1 L or qt of water** **Amount to achieve 4 mg·L^{-1}**	 **Amount to achieve 8 mg·L^{-1}**
Iodine tabs[b] Tetraglycine hydroperiodide Emergency drinking water germicidal tablet Potable aqua Globaline	0.5 tab (or 1 tab in 2 L)	1 tab
2% iodine solution (tincture)	0.2 mL	0.4 mL
	5 drops[c]	10 drops
10% povidone-iodine solution[d]	0.35 mL	0.70 mL
	8 drops	16 drops
Saturated solution: iodine crystals in water[e]	13 mL	26 mL
Chlorination techniques[f]	Amount to achieve 2 mg·L^{-1}	Amount to achieve 5 mg·L^{-1}
Sodium hypochlorite (household bleach 5%)	1 drop	0.1 mL 2 drops
Sodium hypochlorite (household bleach 8.25%)	1 drop (in 2 L)	1 drop
1% bleach (CDC-WHO Safe Water System)[g]	4–5 drops	8–10 drops
Calcium hypochlorite[h] (Redi Chlor [0.1-g tab])	Cannot use in small quantities for low concentrations	0.25 tab
Sodium dichloroisocyanurate (NaDCC)[i] (Aquatab, Kintab)	0.25 tab of 8.5 mg NaDCC (may be impractical)	0.5 tab (8.5 mg NaDCC)
Chlorine plus flocculating agent (C-F)	Not practical for small volumes	0.5 tablet per gal yields 5 mg·L^{-1}

[a] World Health Organization recommends only for short-term emergency use.

[b] Iodine tablets were developed by the military with the criteria that they will disinfect water, including for *Giardia*, with a short contact (holding) time of 10 min because troops in the field may not wait longer. This high concentration is not necessary for field disinfection of clear water; it is preferable to target 4 mg·L^{-1} and wait longer. Additionally, the recommendation to use 8 mg·L^{-1} for cloudy water will result in poor taste, so it is recommended to clarify the water first.

[c] Measure of a drop varies from 16–24 gtt·mL^{-1}, standard 20 gtt·mL^{-1} is used here.

[d] Povidone-iodine solutions release free iodine in levels adequate for disinfection, but scant data are available (see text).

[e] A small amount of elemental iodine goes into solution (no significant iodide is present); the saturated solution is used to disinfect drinking water. Water can be added to the crystals hundreds of times before they are completely dissolved.

[f] Can easily be adapted to large or small quantities of water. Simple field test kits or swimming pool test kits with color strips are widely available to ensure adequate residual chlorine. In usual situations, EPA recommends a target residual of 4 $mg \cdot L^{-1}$. For household use, the CDC recommends <2 $mg \cdot L^{-1}$. Many of the recommended emergency doses exceed this threshold.[97] For treatment of large volumes, see formula to calculate in Lantagne (2008).[20]

[g] Safe water system for long-term routine household point-of-use water disinfection recommends a hypochlorite dose of about 2 $mg \cdot L^{-1}$ in clear water and 4 $mg \cdot L^{-1}$ in slightly turbid water. This results in a low yet effective target residual concentration but requires testing in a particular water source to ensure sufficient residual.

[h] Stable, concentrated (70%), dry source of hypochlorite that is used for chlorination of swimming pools. Multiple products available in various size tablets or granular form. Best formulation for large quantities of water.

[i] Available in different strengths to treat different volumes of water. Check packaging to determine proper dose.

Table 6.

Recommendations for contact time using halogen disinfection in the field

Concentration of halogen	**Contact time (min) at various water temperatures**		
	5°C (41°F)	**15°C (59°F)**	**30°C (86°F)**
2 ppm	240	180	60
4 ppm	180	60	45
8 ppm	60	30	15

Concentration and contact time are based on the most resistant organism, which is the *Giardia* cyst. These are well beyond the time needed to kill bacteria and viruses. These contact times have been extended from the usual recommendations in cold water to account for the extended inactivation time required in very cold water and for the uncertainty of residual concentration.

Table 7.

Summary of field water disinfection techniques

	Bacteria	Viruses	Giardia/Ameba	Cryptosporidium	Nematodes/Cercarea
Heat	+	+	+	+	+
Filtration	+	+/–[a]	+	+	+
Halogens	+	+	+	-	+/–[b]
Chlorine dioxide and photocatalytic	+	+	+	+	DNA[b]

DNA, data not available.

[a] Most filters make no claims for viruses. Ultrafiltration with hollow fiber technology and reverse osmosis is effective.

[b] Eggs are not very susceptible to halogens but have very low risk of waterborne transmission. No data available for photocatalytic disinfection.

Table 8.

Efficacy and effectiveness of point-of-use technologies for 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	

SODIS, solar disinfection.

Data from multiple studies, analyzed and summarized by Sobsey et al (2008).[165]

Data also from references[47,166-168] and Table 7.8 in WHO (2011).[26]

[a] Skilled operators using optimal conditions and practices (efficacy); log reduction: pretreatment minus posttreatment concentration of organisms (eg, 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 vary with consistency and correct use of technique, integrity of techniques (eg, cracked filter), and other household sanitation measures.