

Evaluation of the purification capacity of nine portable, small-scale water purification devices

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Abstract A test was performed to evaluate the microbial and chemical purification capacity of nine portable, small-scale water purification filter devices with production capacity less than 100 L/h. The devices were tested for simultaneous removal capacity of bacteria (cultured *Escherichia coli*, *Clostridium perfringens*, *Klebsiella pneumoniae* and *Enterobacter cloacae*), enteric protozoans (formalin-stored *Cryptosporidium parvum* oocysts), viral markers (F-RNA bacteriophages) and microcystins produced by toxic cyanobacterial cultures. In general, the devices tested were able to remove bacterial contaminants by 3.6–6.9 log₁₀ units from raw water. Those devices based only on filtration through pores 0.2–0.4 μm or larger failed in viral and chemical purification. Only one device, based on reverse osmosis, was capable of removing F-RNA phages at concentrations under the detection limit and microcystins by 2.5 log₁₀. The present study emphasised the need for evaluation tests of water purification devices from the public safety and HACCP (Hazard Analysis and Critical Control Point) points of view. Simultaneous testing for various pathogenic/indicator microbes and microcystins was shown to be a useful and practical way to obtain essential data on actual purification capacity of commercial small-scale drinking-water filters.

Keywords Coliform bacteria; *Cryptosporidium parvum*; F-RNA bacteriophages; microcystin; water purification device

Introduction

Several products by different manufacturers are commercially available for drinking-water purification. Drinking-water safety is a serious health issue, especially under field conditions in which no organised water supply is available and drinking water must be obtained from various, usually faecally or otherwise contaminated, surface water sources. These devices, mostly based on filtration through ceramic or membrane filters, are needed especially by soldiers, hikers or workers from aid agencies operating in primitive wilderness or following a natural disaster (Backer, 2002). Similar filters are also marketed for point-of-use, to single households. Advertising of the water purification capacity of the devices is, in general, very optimistic. Therefore, to ensure consumer safety it is essential to compare the microbial and chemical purification capacity of different devices through independent evaluation tests (Monjour *et al.*, 1990; Eisenberg *et al.*, 2001). Data are available on the purification capacity of some filter devices, but are usually based only on their capacity to remove single microbial groups, e.g. *Escherichia coli*, coliforms or *Cryptosporidium* oocysts (Raynor *et al.*, 1984; Schlosser *et al.*, 2001). Only one previously published study described the simultaneous purification of several microbial groups by a single device (Grabow *et al.*, 1999). The aims here were (a) to obtain reliable data on the purification capacity of several devices to simultaneously remove indicator bacteria, *Cryptosporidium*

oocysts, F-RNA bacteriophages and cyanobacterial microcystins and (b) to assess the evaluation procedure itself.

Materials and methods

Water purification devices

The devices were selected among products commercially available, based on the suitability for field operation. It was not intended to include all commercially available devices but to obtain a representative selection of various types of filter and, thus, a general overview of their purification capacities. All of the nine devices tested (Table 1) from six manufacturers were portable (weight <10 kg) and functional without electricity or chemical supplementation.

Seeded raw water

Raw water was taken from natural surface water (a lake) into a plastic 700 L container, with the contaminants added and mixed into the container during filling. The bacterial strains *Escherichia coli* ATCC 25922 and 36 (culture collection of Helsinki University, HU); *Klebsiella pneumoniae* 26 (HU) and *Enterobacter cloacae* 87 (HU) were cultivated separately in sterile 200 mL glass bottles in liquid brain-heart-infusion (BHI) medium and incubated aerobically at 35°C for 24 ± 2 h. *Clostridium perfringens* ATCC 12916 was grown in BHI medium and incubated anaerobically under a 2-cm-thick layer of vegetable oil at 35°C for 24 ± 2 h. The undiluted bacterial suspensions in BHI-broth, formalin-stored *Cryptosporidium parvum* oocysts (concentration of oocysts 10⁸/8 mL; Waterborne; New Orleans, USA) and F-RNA bacteriophages (MS2, Haartman Institute) in physiological saline solution were added to the raw water. Furthermore, the raw water was seeded with deep-frozen and thawed microcystin-producing cyanobacterial cultures (*Anabaena* and *Microcystis*, Finnish Environment Institute). The concentrations of the contaminants were adjusted to represent microbially heavily polluted surface water with high nutrient level and cyanobacterial blooming. The counts of contamination microbes, concentration of

Table 1 Water purification devices in the evaluation test

Device	Manufacturer	Purification technique*	Production capacity (L)*	
			L/h	L/lifetime
Survival Straw	Ingram Water and Air, Paducah, USA	Filter, bacteriostatic release	5	18,500
Katadyn Combi	Katadyn Products Inc., Wallisellen, Switzerland	Ceramic filter (0.2 µm), activated carbon	72	50,000
Katadyn Pocket	Katadyn Products Inc., Wallisellen, Switzerland	Ceramic filter (0.2 µm)	72	50,000
Katadyn Survivor MROD-35	Katadyn Products Inc., Wallisellen, Switzerland	Reverse osmosis	4.5	
MiniWorks	Mountain Safety Research, Seattle, USA	Ceramic filter (0.2 µm), activated carbon	40	
WaterWorksII	Mountain Safety Research, Seattle, USA	Ceramic filter (0.2 µm), activated carbon, membrane filter (0.2 µm)	40	
Nerox filter	Nerox Filter Oy, Tampere, Finland (Plastec AS, Gjøvik, Norway)	Membrane filter (0.4 µm)	5	2,500
Safe Water In-line Hydration filter	SafeWater Anywhere, Ashland, USA	Metal prefilter (25 µm), silver-coated primary filter (2 µm)	5	750
WalkAbout Microfilter	Sweet Water, Cascade Designs, Seattle, USA	Filter cartridge (0.2 µm)	54	460

* Data according to the manufacturers' product packaging or in general marketing material, if available

microcystins and physico-chemical parameters in raw water (influent) were determined from three separate subsamples.

Use of devices and sampling

The devices tested were used manually following the instructions given by the manufacturer. Before the purification of the seeded raw water, 1–2 L of sterile water was rinsed through each device. A total of 15 L of purified water was produced, or less if filter blockage occurred. Devices intended for use by direct suction were used by vacuuming the raw water through the devices with a vacuum pump at 0.6 atmospheric (0.61×10^5 Pa) pressure. The purified water was collected into a sterile 20 L container. Samples for bacteriological (1 L), viral (10 mL), microcystin (200 mL) and protozoal (remaining purified water) analyses were taken from this processed water (effluent).

Microbiological and chemical analyses

All bacteriological (coliforms, *E. coli* and sulphite-reducing clostridia) and physico-chemical parameters (turbidity, pH, conductivity, KMnO_4 count, nitrate and nitrite concentrations) were analysed using national SFS standards (Finnish Standards Association SFS, 1995). *C. parvum* oocysts were concentrated from 3–10 L samples by filtering through a polycarbonate filter. The concentrates were further purified using immunomagnetic separation (IMS; Rimhanen-Finne *et al.*, 2002). After IMS, a 50 μL volume was taken for immunofluorescence assay (IFA) microscopy. Oocysts were detected with direct IFA using an Aqua-Glo G/C Kit (Waterborne; New Orleans, USA). The slides were screened with an epifluorescence microscope at 200 \times magnification and those particles with green fluorescence confirmed with a magnification of 400 \times . Objects of ovoid or spherical shape and diameter of 4–6 μm were recorded as *Cryptosporidium* oocysts. The presence of F-RNA bacteriophages was analysed according to ISO 10705-1 (ISO, 1995) from 10 mL water samples. Additionally, some devices were tested separately only for their capacity to remove MS2 phages. Samples for microcystins were treated and analysed as previously described (Lahti *et al.*, 2001; Rapala *et al.*, 2002) using a commercial ELISA test (EnviroGuard microcystins plate kit; Strategic Diagnostics Inc., Newark, DE, USA).

Determination of purification capacities

The purification capacities were calculated as logarithmic (\log_{10}) reductions of analysed parameters between concentrations in raw water and purified water. The raw water concentrations were calculated as the arithmetic mean of three separate samples from each analysis. \log_{10} reduction was calculated with the following formula:

$$\text{Log}_{10} \text{ reduction} = \log_{10}(N_i/N_e)$$

where N_i was the concentration in raw water before purification (influent) and N_e was the concentration in purified water after purification (effluent). If no target organism was detected in purified water the \log_{10} reduction was calculated assuming one organism in purified water per analysed volume. *Cryptosporidium* oocysts and F-RNA bacteriophages were reported using a two-step scale (–, not detected; +, detected); furthermore, for some devices F-RNA bacteriophages were analysed separately and their concentration in effluent reported as PFU/mL. Total microcystin concentrations were recorded as microcystin-LR equivalents in $\mu\text{g/L}$.

Results and discussion

In general, the devices tested were able to remove bacterial contaminants: *E. coli*,

K. pneumoniae, *E. cloacae* and sulphite-reducing clostridia from raw water, but failed in the purification of bacteriophages used as model for viruses and in removal of microcystins (Table 2). Water purification based purely on physical filtration was not able to remove viral contaminants or cyanobacterial microcystins from heavily polluted raw water. Lower numeric \log_{10} removal of sulphite-reducing clostridia than that of coliforms was most probably only due to the lower contamination level of clostridia than coliforms in raw water. Removal of *C. parvum* oocysts was in general similar to removal of bacteria, but some devices failed in purification and passed some oocysts into purified water.

Taking into account the purification techniques of individual filters, the results coincided with their theoretical purification capacities and with the results of earlier studies on some other drinking-water purification filters (Schlosser *et al.*, 2001). Testing of water purification filters simultaneously with indicator bacteria, bacteriophages as viral markers, protozoal oocysts and microbial toxins produced valuable information for safety assessment purposes.

Comparison of marketing information with the test results revealed that some devices were advertised to be more efficient in removal of microbes and toxins than was found in our studies, while information from some manufacturers coincided loosely with the test results. Some manufacturers stated in the marketing information that their product was able to decrease the counts of all bacteria (including *E. coli*) by 2–6 \log_{10} units, and parasites (including *C. parvum* oocysts) by 2–4 \log_{10} units. Others gave only a general statement of removal capacity or stated that the device was not able to remove viruses. Only one device based on reverse osmosis was advertised to remove “harmful viruses and chemicals from raw water”. This device indeed was the only one that removed F-RNA phages to under the detection limit and microcystins to under the guide value 1 $\mu\text{g/L}$ for microcystin in drinking water given by the World Health Organization.

Our earlier unpublished studies using the same procedure for testing of three large-scale water purification devices (production capacity over 1,000L/h) for field operations gave results that supported the need for a multibarrier concept in drinking-water production. Purification capacities for coliforms and *E. coli* were 4.5–6.5 \log_{10} units, F-RNA phages

Table 2 Purification capacities of evaluated water purification devices¹

Device	Log-reduction ²						
	Coliforms	<i>E. coli</i>	Clostridia	Turbidity	Microcystin	<i>C. parvum</i> oocysts ³	F-RNA phages ⁴
Survival Straw	0.5	0.5	0.7	0.2	0.1	+	+
Katadyn Combi	>6.9 ⁵	>6.9 ⁵	>1.8 ⁵	1.1	0.2	–(<5.1 ⁵)	+(2.7)
Katadyn Pocket	>6.9 ⁵	>6.9 ⁵	>1.8 ⁵	1.1	0.2	–(<5.1 ⁵)	+(3.3)
Katadyne Survivor MROD-35	4.2	4.2	>1.8 ⁵	1.6	2.5	–(<5.1 ⁵)	–(>5.8 ⁵)
MiniWorks	6.9	>6.9 ⁵	>1.8 ⁵	1.3	0.3	+	+
WaterWorksII	>6.9 ⁵	>6.9 ⁵	>1.8 ⁵	1.6	0.3	–(<5.1 ⁵)	+(5.0)
Nerox filter	>6.9 ⁵	>6.9 ⁵	>1.8 ⁵	1.0	0.1	Not tested	+(5.8)
Safe Water In-line Hydration filter	>6.9 ⁵	>6.9 ⁵	0.3	0.04	0.3	+	+
WalkAbout Microfilter	3.6	>6.9 ⁵	>1.8 ⁵	1.4	0.1	Not tested	+

¹ Microbiological and physicochemical properties of raw water used in test: *E. coli* 7.9×10^6 CFU/100 mL; sulphite-reducing clostridia 39 CFU/100 mL; theoretical count for *C. parvum* oocysts 1.4×10^5 /L; F-RNA phages 4.3×10^5 PFU/mL; microcystin 16.5 $\mu\text{g/L}$; temperature 15°C; turbidity 4.4 FNU; pH 5.4; conductivity 51.3 $\mu\text{S/cm}^2$; KMnO_4 130 mg/L; NO_3^- 2.7 mg/L; NO_2^- 0.02 mg/L

² Calculated as $\log_{10}(N_i/N_e)$ where N_i = count/value in raw water and N_e = count/value in purified water

³ Result for *C. parvum* oocysts in purified water given as – (not detected) or + (detected)

⁴ Result for F-RNA phages in purified water given as – (not detected) or + (detected) (\log_{10} reduction obtained from separate phage removal test)

⁵ Not detected in purified water and \log_{10} reduction calculated assuming one particle count in purified water

4.2–4.4 log₁₀, for microcystins 2.0–2.8 log₁₀ (concentration in purified water <0.09 µg/L) and all devices removed *C. parvum* oocysts under the detection limit. All large devices tested were based either on prefiltration, reverse osmosis and ultraviolet radiation or on prefiltration, ozonation, sand and activated carbon filtration. In the present study the construction or robustness of each device was not tested. Information on this aspect could be obtained through operational tests under various climatic and environmental conditions. In addition to the fundamental purification technique, the construction of devices and cleaning and maintenance procedures may play an important role in the final purification capacity.

Conclusions

The test results gave comparable data on the purification capacity of the various devices. Results showed sufficient capacity (3.6–6.9 log₁₀) for removal of bacterial contaminants from raw water, but showed deficiencies, especially in the removal of F-RNA phages and microcystins, if purification is based only on filtration through pores 0.2–0.4 µm or larger. Only one device, based on reverse osmosis, was capable of removing F-RNA phages to below the detection limit and microcystins by 2.5 log₁₀. This, and earlier studies, emphasised the need for evaluation tests of water purification devices from the public safety and HACCP points of view. The procedure of the test performed with simultaneous analysis of various microbes and cyanobacterial toxin was shown to be a useful and valuable way for evaluation of a single or several water purification devices.

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